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## THE SPIRIT OF ASTRONAUTICS IN GERMANY IN THE LAST 15 YEARS


By Hans K. Kaiser*


Very little has become known abroad during the last 15 years about the development of the space-flight idea in Germany. By the end of 1929 the renowned journal, *Die Rakete* (The Rocket), appearing in Breslau, had to cease publication because of lack of money. The "Verein für Raumschiffahrt" (Society for Space-Flight, V.f.R.), though for some years carrying on experiments with liquid-propellant rockets, in the aerodrome for rockets in Berlin-Reinickendorf, dissolved in 1934—after the failure of the project of the man-carrying rocket—on account of its lack of means and sad internal disagreements. Thus ended in Germany the first epoch of astronautics, after beginning with too high anticipations, and closing with general disappointment.

The following years elapsed without any creative activity. Some members of the former V.f.R. had foined the "E.V. Fortschrittliche Verkehrstechnik" (E.V.F.V., Registered Society for the Progress in Traffic Technics), which, on a very modest scale, tried to stand for the idea of space-flight, and which, at irregular intervals and in a small edition, issued a primitive information paper, *Das neue Fahrzeug* (The New Vehicle). This society remained for the most part unknown, even among Germans interested in the space-flight idea, until finally it also dissolved.

Nevertheless, not even in these years had the spirit of astronautics died away in Germany. The idea of flight in space having once been roused, enthusiasm for it continued to stir some minds. In Breslau, native town of the former V.f.R., the author tried as far back as 1934/35 to extend the circle of persons interested in the idea, by making speeches. In 1936 he started a team for space-flight within the "Breslauer astronomische Vereinigung e.V." (Society for Astronomy of Breslau). Encouraged by the considerable interest which he met, he founded, together with 11 further adherents of the space-flight idea, the "Gesellschaft für Weltraumforschung e.V." (G.f.W., Society for the Exploration of the Space) in Breslau on 18th August, 1937.

The new society's objects were to be: The union of all persons interested in astronautics, foundation of a scientific library, instruction of the members, publicity for the space-flight idea, financial aid to the work of expert-scientists,


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lectures and publications. As journal appeared—for the first time in 1939—the quarterly review *Weltraum*.

The V.f.R. having been founded in the period of the first great rocket enthusiasm, the difficulties it had to overcome had by far been inferior to those against which the G.f.W. had to fight. The question was to surmount the scepticism of the public, the disappointment of persons formerly interested in the idea, the rejection by scientists, the suspicions of the authorities and lack of means. And yet—owing to the enthusiastic readiness of a group of younger members to stand up for the idea—the revival of the space-flight idea was carried through successfully and in very short a time. The number of members grew quickly, and experts gradually joined. In addition to Breslau, active local groups sprang into existence in Berlin and in Cologne, as well as official agencies in several other German cities. Moreover, it was possible to become connected with foreign countries, such as—in particular—England, U.S.A., France and India. It had been planned for the near future to participate in the international exhibitions which were intended for Cologne and Rome in 1940, and to edit a comprehensive and popular book about astronautics with the collaboration of indigenous and foreign experts, taking into consideration the most recent results of scientific research. Then the war broke out, putting an end to all plans.

Most of the collaborators being conscripted, the G.f.W. had to end its activities in 1940. The influx of persons who wanted to join the society continued, however, and this encouraged the society again to take up activity in the next year. Apart from the journal the members now regularly also got a series of reproductions of speeches. In the meantime the general interest in astronautics had been increased anew by the excellent film, *Weltraumschiff I startet* (Spaceship I Starts), produced by the "Bavaria" under the management of Anton Kutter.

After the directors Hans K. Kaiser, Krafft Ehricke and Fritz Schmidt had taken up duty with the "Heeresanstalt Peenemünde" (Army Establishment Peenemünde), Dr. de Grahl entered the office of president in 1942. He was followed by K. Ehricke in 1944. Because of lack of paper the *Weltraum* was no longer allowed to appear after 1943.

It may be relevant to add to this report some remarks with regard to the work done at Peenemünde, which in the course of the war resulted in important accomplishments in the development of rockets (*vide* "V2"). From the point of view of astronautics this development may be regarded as a detour. There must not be overlooked, however, that, on the other hand, this development brought forth knowledge and results such as never could have been expected, had rocket science developed in a normal way. There was many a collaborator at Peenemünde for whom the sublime goal of space-flight stood behind the actual development of rockets, as I know from talks I had with Dr. W. v. Braun, technical manager of the "Heeresanstalt" and former member of the managing committee of the V.f.R. This is also proved by the numerous admissions of new members to the G.f.W. from this very Peenemunde.

After Germany's collapse in spring, 1945, the G.f.W., too, had to stop activity, but the courage of the champions for the space-flight idea proved to

be unbroken. No sooner had the first postal and traffic communications been re-established than the persons interested in the idea sought to get into contact with one another, and inquired into the possibilities of continuing the interrupted work.

The situation offered an almost hopeless aspect. The society's property had got lost in Breslau, the valuable library and all stocks of material had been destroyed by air attacks. Many of the society's members had been killed during the war, and others were missing in the lost eastern provinces. Several others had made contracts as to their occupation abroad, for which reason it was no longer possible to depend on their collaboration in the recovery of the organization in Germany. Among them has been Herr K. Ehricke, last president of the G.f.W. Here are the names of a few members, renowned also abroad, who died during the war and in the subsequent years: Klaus Riedel, who had been one of the foremost engineers at the "Raketenflug Platz," died by an accident* at Peenemünde on 18th July, 1944. Dr. Ing. W. Hohmann, author of *Die Erreichbarkeit der Himmelskörper* (The Attainability of the Celestial Bodies), died during an air attack on Essen in March, 1945. Dr. de Grahl, former president of the G.f.W., died in Berlin in autumn, 1945. In autumn, 1946 died Hanns-Wolf v. Dikhuth-Harrach, former president of the E.V.F.V.,and on 27th December, 1947, Johannes Winkler, founder of the V.f.R. and editor of the periodical, *Die Rakete*, died at Braunschweig.

As it proved to be impossible to get a licence for the whole of Germany for the G.f.W., independent astronautical societies were established in the different zones, working to the same end, and in close contact with one another. First a "team for space-flight" (Arbeitsgemeinschaft für Weltraumfahrt) sprang into existence at the observatory of Treptow (Berlin), after that the "Südwestdeutsch Gesellschaft für Weltraumforschung" (Society of south-western Germany for space exploration) was founded at Frankfurt am Main, as well as the G.f.W. at Stuttgart, which as yet has been the most busy of all. A north-western German society for space-flight (Nordwestdeutsche G.f.W.) domiciled at Stade, is about to be founded for the British zone. It is the object of all these societies to promote and propagate the idea of space-flight, and to contribute to its future realisation within the limits, though narrow, of the respective possibilities in Germany today.

At the same time the closest possible contact with foreign circles interested in astronautics is desired.

By the German currency-reform of June, 1948, these young societies have been struck by a grave economic crisis, which seriously endangers their existence. We still hope, however, that by their joint efforts our enthusiastic and plucky collaborators will succeed in overcoming that danger, and that by our journal, *Weltraum*, the re-edition of which is planned for the near future, it will be possible to announce to the world that in Germany, too, the idea of astronautics is still alive.

[Translation from the German by Hermine Richter, Dillingen Danube.]

* We understand this was a road accident.—Ed.

# ROCKETS IN CIRCULAR ORBITS

By Kenneth W. Gatland

## Introductory

It has been emphasised repeatedly that atomic energy as we visualise it to-day is not the key to *easy* release from the Earth's gravitational field. An inert working fluid, such as liquid hydrogen, replaces the fuel and oxidant of the chemical rocket, and a "high-temperature pile" (expanding the gas through a conventional nozzle system), the "combustion chamber." Still, 80 to 90 per cent. of the vessel must comprise propellant, and despite a predicted doubling of the exhaust velocity over present chemical combinations, heavier component weights in power-unit and tanks—plus a formidable new item, *shielding*—suggest the following main requisites of the design:—

(*a*) A high initial velocity to surmount the denser regions of the atmosphere and achieve "release velocity" in the minimum time compatible with crew well-being.

(*b*) Efficient propellant storage.

(*c*) An economic shielding pattern as protection from radiation.

It will be apparent that (*a*) and (*b*) are the two factors which have always been essential in our pre-atomic concepts (of pencil-like hull configuration) and the final consideration (*c*) fits ideally into this, since a small cross-section of hull with the crew chamber and tanks placed in the radiation shadow, will permit a maximum of shielding.

The fact that an atomic rocket will leave radio-activity behind in the atmosphere makes launching one of the major problems. There are, one supposes, three possibilities:—

(*a*) Take-off from an area far removed from habitation. If possible, from some natural high level.

(*b*) Take-off by chemical booster rockets.

(*c*) Assembly of the vessel in an orbit outside the atmosphere using parts prefabricated on Earth and ferried out in successive flights by chemical rockets.

In practice, however, the project would be developed in a combination of at least (*b*) and (*c*) so that the atomic power-unit is placed in the orbit by its own power, in conjunction with a chemical booster, with assembly and servicing of the final vessel by tender rockets.

The latter prospect alters the picture completely. When we arrive at the stage where guided missiles can penetrate into space and be established in an orbit around the Earth—and, equally important, be retarded into a safe landing—then the further step of *manned* orbiting rockets should not be far from reach. Such a technique has often been suggested but the purpose of this present paper is to argue that it still merits consideration, even if some form of atomic propulsion is available.

**Orbits in the Earth-Moon Field**

To appreciate how this condition of power-less motion can be achieved, it will be convenient to re-state the case mathematically. Thus, for a rocket to balance the gravitational attraction of the Earth in a circular orbit outside the atmosphere, its velocity ($v$) will be in accordance with the following equations, where:—

$M$ = Final rocket mass.

$r$ = Radius of orbit from Earth's centre.

$R$ = Radius of Earth.

$g_o$ = Gravitational acceleration at Earth's surface.

$$\text{Centrifugal force} = \frac{Mv^2}{r} \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

Gravitational force (weight of rocket in orbit)

$$= Mg_o\left(\frac{R}{r}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Equating (1) and (2) for balance:—

$$v = \sqrt{\frac{g_o R^2}{r}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

The period of one revolution of the rocket in the orbit is then given by:—

$$T = \frac{2\pi r}{v}$$

$$= \frac{2\pi}{R}\sqrt{\frac{r^3}{g_o}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

The total energy per unit mass (E) required to place the rocket in the orbit is the sum of the kinetic and potential energies (K and P respectively) involved; thus, from basic principles:—

$$K = \tfrac{1}{2}Mv^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

while, if $x$ represents the distance from the Earth's centre, the rate of increase of P with $x$ is given by:—

$$\frac{dP}{dx} = Mg_o\left(\frac{R}{x}\right)^2$$

Hence, the total potential energy of the rocket in its orbit is:—

$$P = Mg_oR^2\int_{x=R}^{x=r}\frac{1}{x^2}\cdot dx\,.$$

$$= Mg_oR\left(\frac{r-R}{r}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Finally, $E = \frac{K + P}{M}$; therefore from (3), (5) and (6) we have:—

$$E = \frac{g_o R^2}{2r} + g_o R\left(\frac{r - R}{r}\right)$$

$$= \frac{g_o R}{2r}(2r - R) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

No account has been taken in the above of the possible contribution of the Earth's peripheral velocity at the surface to the required total velocity.

From these equations, it can be found that if the rocket is to be established in an orbit (in the plane of the equator) such that it appears stationary with respect to a point on Earth, it will be located at a distance of 35,900 kms. (22,300 miles) from the surface—about one-tenth the distance to the Moon. The orbital velocity will be 3,070 m./sec. (10,100 ft./sec.), and the total energy per unit mass, $5{\cdot}8 \times 10^7$ kg.m./kg. ($2 \times 10^{10}$ ft.lb./slug).

If it were possible to place the orbit at 322 kms. (200 miles) altitude, the power requirements are then much reduced, the total energy per unit mass becoming $3{\cdot}3 \times 10^7$ kg.m./kg. ($1{\cdot}1 \times 10^{10}$ ft.lb./slug), and the orbital velocity, 7,750 m./sec. (25,400 ft./sec.). The period of revolution is 1·51 hours.

Detailed analysis will be required to select the best altitude and to determine the optimum trajectory for entering the orbit. For the purpose here considered, there is, of course, no special merit in the so-called "stationary orbit" of a 24-hour period.

**The Landing Question**

Whatever the method of launching, it appears certain that atomic energy in itself will not suffice for landing. Attention has been drawn earlier[1] to the possibility of rising dust clouds, due to the retarding exhaust being radioactive during landing manoeuvres on the Moon.

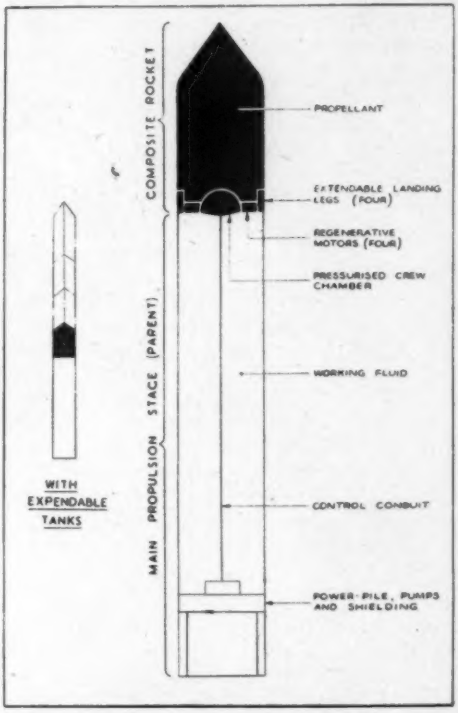
We have thus the prospect of powering our space-vessels partly by atomic and partly by chemical means, with separate power and propellant systems and all the additional complication in layout and control that these incur. The suggestion of taking an inactive plutonium reactor and its attendant shielding down on to the surface by chemical motors—and taking off again—naturally involves a considerably enlarged mass-ratio. It is difficult to visualise anything but a lengthy cylindrical hull as the result, to increase the risk of toppling and further complicate the landing gear arrangement; naturally, this reflects equally unfavourably at the launching end.

Despite appearances, stern-first alighting—in conjunction with a radar altimeter—is far the more likely to succeed in practice. However, even though the greater mass is disposed in the stern, the high-fineness-ratio hull does not quite give the assurance that uneven contact with the surface will not result in disaster. A great deal of research will be needed to produce efficient compensatory, shock-absorbing landing legs, but even so, the ideal will be a relatively short hull configuration. We are therefore confronted with two rather different ideal shapes for the launching and landing, with little room for compromise either way.

There is, however, a possibility by which the situation may be retrieved. If an independent, chemically-fuelled rocket could be built into the vessel so that after being established in a "circular orbit" it was free to *leave*, a stern-first landing might then be entirely feasible.

**The Composite Landing Rocket**

A diagrammatic impression of how such a combination rocket might be evolved is given in the figure. It will be apparent that incorporation of the




Schematic diagram of ground-launched space-vessel with composite landing rocket.

composite rocket does not greatly interfere with accepted layout nor materially affect the mass-ratio.

A single crew-chamber built into the composite craft (with electrical intercommunication to the reactor and an automatic means of re-coupling) would serve under both conditions of flight—the two rockets in combination or the small craft operating independently. The main components in the latter might then be the following:—

(*a*) Pressurised crew chamber—and airlock (concentric with the major axis and situated against the rear bulkhead to facilitate entry and exit).

(*b*) Four rocket units of conventional design, equally pitched on a circle outside the crew chamber (with pivoting motors or exhaust vanes, in conjunction with pitch and azimuth gyros, for lateral stability in landing and re-linking with the parent. Also, separate torque motors for imparting, or damping out, axial rotation).

(*c*) Four extendable landing legs.

A homing beacon would enable the composite rocket to be brought back into the vicinity of the parent with comparative ease. Final alignment and re-connection might then be obtained by a magnetic system* (possibly an adaptation of the Hughes induction bridge) working on the principle of deformation of field in conjunction with servo-control units in the composite craft. Small peroxide-permanganate rocket motors could serve for the control elements by which the craft is pushed bodily sideways, moved rearwards, or the rate of hull rotation increased or decreased.

Propellant for the composite craft might usefully be liquid oxygen and liquid hydrogen, since the latter is the working-fluid for the reactor and its tanks can be utilised as a reservoir during transfer from expendable tanks,[1] if these are fitted.

Up to the attainment of release velocity, propellant would be pumped out of the tanks in the main propulsion stage. These would remain filled by propellant flowing through the tank space in the composite rocket from the expendable tanks at the nose, so that when the vessel attains the velocity of gravitational release and the motors cut-out, the tanks of both the composite rocket and the section below it remain full. Since an intermittent means of re-liquefaction of the propellant would probably be necessary (working to a certain pressure-rise in the tanks), the turbines of these liquefaction units —fitted in the composite craft—might also serve to work the engine pumps during the time the small rocket is operating independently.

**The Crew Chamber**

It is assumed that the vessel would be stabilised by axial rotation to approximate 1 g. on a radius arm of 11 feet. This is the figure to which the B.I.S. "cellular" rocket[2] was designed and which will also be assumed here. A standing position relative to the "artificial floor" (*i.e.* the walls at right angles to the true floor) would subject the head to 5/11 g.—a variation of $6/11 = 0{\cdot}55$ g. At a normal sitting attitude (the distance between the head and feet being approximately 4 feet), g. = 1 at feet and 7/11 at head with a variation of $4/11 = 0{\cdot}36$ g.

An improvement would be for the crew to be carried on separate cradle "chairs" equally pitched around the cabin and which can pivot from arms extending from the axis. Thus, each man faces inwards and will automatically change his attitude according to the condition of simulated gravity prevailing,

* Radar linkage might not prove sufficiently responsive at a few feet to zero, whereas this range would be effective in a magnetic system.

due to thrust or centrifugal force. The back supports of the cradles will be pressed against the true floor during the initial thrust period. In free-flight, with the vessel rotating, centrifugal force will have moved each cradle in an arc through 90° so that the men are vertical to the true floor. This would overcome the "g" differential between head and feet, or as nearly as possible.

There is no fundamental objection to a shorter axis of rotation if the body is under uniform "g" and the crew are accommodated in the manner described: it simply means faster spin. In the Smith–Ross man-carrying rocket,[3] for example, the seating radius is little more than $2\frac{1}{2}$ feet.

Certainly there is no call for the radius arm of 30 feet which E. A. Pecker postulates in his recent paper[4] and which results in a disc-like conception of the space-vessel. The design is considered independent of aerodynamics for vertical ascent, it being assumed that "the craft rises to an altitude of 100 miles at the rate of 100 m.p.h., or less," and it is emphasised that the shape provides a "high-speed" section for horizontal flight in atmosphere.

Instead of basing the investigation on the power-unit and relating the other considerations, Mr. Pecker has satisfied what he feels to be the major physiological requirements with almost complete disregard of other essential factors. His assumption that "an adequate power supply of not unreasonable dimensions" is available for interplanetary flight at once relegates the discussion to the academic and when it is stated that the final dimensions arrived at for the disc-rocket give a diameter of 70 feet and a thickness of 10 feet, and that the volume of the personnel quarters (14,000 ft.$^3$) exceeds the combined space for power-unit, propellant and accessories (12,500 ft.$^3$), these remarks can be better appreciated.

The design forfeits the one important factor of achieving minimum "g" loss in building up to final velocity in the shortest interval. Again, if atomic powered, shielding against radiation is required and with so large a cabin diameter, it would take an inordinate quantity to give the necessary protection. The suggested use of television is another point with which many will disagree. This method does not permit the observation of stars because of insufficient sensitivity in the iconoscope and limitations of grain size in this device and in the viewing screens. The more practical solution at present would seem to be an optical device on the basis of the stroboscope (such as the "coelostat,"[5] developed by the B.I.S., in pre-war days) which gives apparently stationary vision from a rotating cabin. The crew would, however, be relieved of much strain if the flight was under direct telecontrol from the Earth.

### Orbital "Escape" Technique

To revert now to the combination rocket, there is an even more encouraging outlook. Once the main propulsion stage (parent) is established in an orbit around the Earth—whether it is built *in situ* or propelled out in convenient sections—we have the prospect of maintaining it in space at both ends of the flight, and landing by the comparatively small chemically-fuelled composite craft. This at once satisfies the question of radio-activity in the atmosphere and in dust raised on the Moon by the exhaust. Moreover, since each time a flight is made the heavier component weights (reactor and shielding) are

already several hundred miles from the surface and travelling at a high fraction of the final velocity, a considerably reduced mass-ratio would be possible and step design, as a main feature, made unnecessary. On this basis, there seems no definite reason why interplanetary flight should not begin even *without* atomic drive. The effect of assembling the parent in an orbit is to build up energy and its maintenance in space provides a valuable potential which is always available.

Obviously there are several methods whereby the scheme could operate. The composite craft, for example, might employ expendable tanks to achieve orbital velocity while maintaining its own fuel capacity, or propellant transfer might be arranged from tender rockets (these, conceivably, with wing attachments) which, in any case, would be required to fuel and service the parent. The parent itself could perhaps carry a reserve of propellant for later transfer into the composite rocket for the Earth landing.

**Conclusions**

With special regard to a *chemical propellant* system (but with application also to atomic drives of the future), it is suggested that orbital escape offers the following advantages:—

(*a*) A substantial potential energy toward gaining "release velocity" is stored by first establishing the parent in a "circular orbit" around the Earth and linking the composite craft (containing the crew) in a second stage.

(*b*) The vessel is accessible from the surface for fuelling, etc., and therefore *supports itself only from the time it leaves the orbit* when, in effect, the flight is commenced. (The greater proportion of the total propellant entailed in the project is consumed in obtaining the orbital condition.)

(*c*) The composite craft, used for landing while the parent remains in an orbit around the visited body, minimises the risk of toppling and due to its smaller mass offers valuable propellant economy.

(*d*) The parent craft (once established in space) will not normally return to the surface and will thereby retain the energy potential for successive flights.

(*e*) The overall mass-ratio is reduced by smaller energy requirements in the separate rocket systems.

(*f*) Step construction (as a main feature) is unnecessary and both component rockets can be re-used with maximum utility.

(*g*) The orbit is ideal for the storage of "low boiling point" propellant where it may be kept without deterioration.

(*h*) A less intricate and costly ground-launching installation is involved.

(*i*) There are no major hazards introduced in launching and operation near the Earth's surface.

It is not suggested that this technique presents a ready solution though, in the author's opinion, it does bring space-flight more into the realm of possibility *within* present engineering standards.

Investigation is suggested along the following lines:—

(*a*) Detailed analysis of orbiting "escape" rockets and determination of optimum altitude.

(*b*) Retard and landing techniques for man-carrying orbiting rockets.

(*c*) Automatic coupling and intermediate stabilisation methods for rockets linking in space.

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# THE ATOMIC ROCKET—4*

By L. R. Shepherd, B.Sc., A.Inst.P., and A. V. Cleaver, A.R.Ae.S.

## 6.—Further Possibilities: the Ion Rocket

In the preceding sections, we have seen that the atomic rocket using nuclear fission to heat up its propellant is a scheme appearing to offer great promise; this promise is somewhat dimmed, however, when one comes to consider the practical difficulties of the operating conditions involved. Future discoveries may introduce ways and means of overcoming these difficulties, and hence of realizing the potentialities of such a "thermodynamic" scheme, as it will be called in this section.

A few of these possible developments have already been suggested in Section 5—nuclear fuels of more favourable characteristics, materials of immense strength and heat-resisting properties, design of the reactor so that energy transfer occurs by unorthodox methods, and so on. It is very important, in forming a fair judgment of the prospects, to preserve a correct sense of perspective. The device under discussion is not one which is expected to be available in final form within, say, the next five years, but rather one which it is hoped may gradually evolve from the developments of the next half-century. It is as well to remember what a lot can happen during such a period—to recall, for instance, the state of science and technology in 1900, and all that has since transpired. Clearly, one should not be limited by the more obvious possibilities; we are free to consider that some quite fantastic new factors *may* arise. Thus, some may care to imagine the consequences of the synthesis of an artificial working fluid of even lower molecular weight than hydrogen. Perhaps more realistically, some consideration might be given to a "pulsing" thermodynamic system; by this is meant one that did not operate under steady conditions of temperature and pressure, but instead in a series of brief "pulses" up to extreme conditions of these quantities, with suitable intervals for cooling in between.

* Concluding part: Parts I, II and III appeared in the Sept. and Nov., 1948, and Jan., 1949, *Journals*. The paper was prepared during the winter 1947–48, when Mr. L. R. Shepherd was engaged in research studies in nuclear physics at the Cavendish Laboratory.

At all events, it is the authors' considered opinion that some form of thermodynamic system will be developed, within the next few decades, which will represent an application of nuclear energy to rocket propulsion giving an exhaust velocity of the order of 10 km./sec. The arguments of Part I give an indication that this will be adequate for multistep interplanetary rockets and it therefore seems likely that such a power plant will be employed on the first exploratory expeditions to other planets in the Solar System. However, one might still feel that such a method fails to exploit all the immense reserves of nuclear energy to a really satisfactory degree, at least for the requirements of truly deep space-flight.

Excursions to either of our nearest planetary neighbours, Mars or Venus, must necessarily involve flights over distances of order $10^8$ km. Given an exhaust velocity of 10 km./sec., and hence a possible characteristic velocity of around 50 km./sec., a spaceship would have very little in hand after allowing for the struggles to and from the Earth's surface. Hohmann has calculated the times occupied by such expeditions, which work out at two to three years and call for accurate timing of take-off and return. These conditions, while not prohibitive, are nevertheless most undesirable, and show the need for much greater characteristic velocities to reduce journey times and provide greater margins. This, in turn, implies the ultimate need for higher exhaust velocities than the approximate 10 km./sec. which can be looked for from the thermodynamic system.

In Part I of this series, it was shown that *very* high exhaust velocities are inadmissible *if high thrusts are simultaneously required*, because of the problems then raised of waste power dissipation. However, in this section it is intended to develop that discussion further, and to show that under certain circumstances it may be possible to obtain exhaust velocities of 100 km./sec. or more.

To expand the arguments previously advanced in connection with equation I. 3, we shall make use of Fig. 5, which shows the variation of specific exhaust power ($p$) with exhaust velocity ($v_e$ km./sec.) and true acceleration ($a$) in gravities. It will be recalled that specific exhaust power was defined as the rate of dissipation of jet kinetic energy per unit time per unit mass of the rocket being propelled, and was given by:—

$$p = 4{\cdot}9 \times 10^3 \times a v_e \text{ kilowatts/tonne.}$$

The total power dissipation in the motor (i.e. the required input to it) will then exceed $p$ to an extent determined by its internal ("thermal") efficiency, and some fraction of this total will be absorbed by the ship itself as waste energy. The permissible limit to the latter quantity (to avoid vaporizing the rocket and all its contents) will then impose, in turn, a limit on the acceptable value of $p$. If we know this limiting permissible value of the specific exhaust power, then the line on Fig. 5 corresponding to it can be selected and the rocket must operate at a combination of exhaust velocity and acceleration to the lower left-hand side of that line. In fact, in accordance with equation I. 3 from which Fig. 5 is plotted, the acceptable exhaust velocity is inversely proportional to the acceleration demanded.

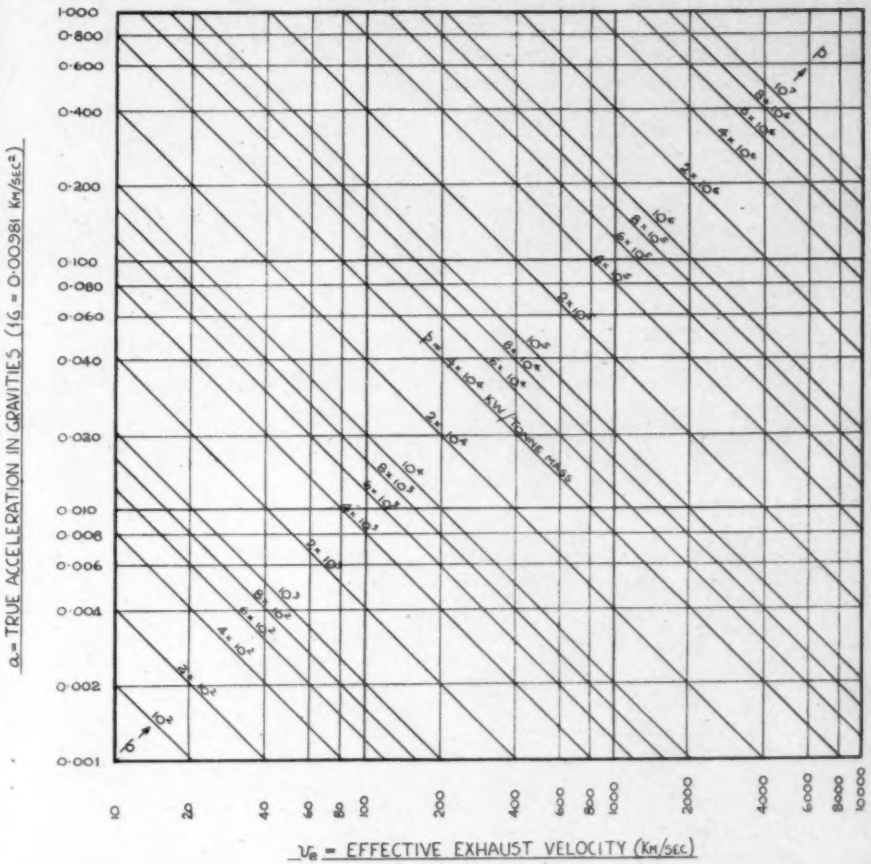


FIG. 5.

Specific exhaust power ($p$) as function of true acceleration ($a$) and exhaust velocity ($v_e$); $p$ in kilowatts per tonne of accelerated mass.

Now, a rocket operating against the Earth's field must have a true acceleration greater than one (surface) gravity, i.e. required $a > 1$, and would probably $\simeq 2$ in practice. However, a rocket moving in field-free space, or in a stable orbit, is subject to no such restrictions; its value of $a$ can be made as small as we please and $v_e$ increased accordingly, without increasing the power dissipation problem. There will, of course, be some limit beyond which $a$ may not be decreased without increasing the transit time of a given flight, despite corresponding improvement in $v_e$. However, we can say that flights to the

inner planets need not call for values of $a$ greater than 0·01, while to the outer planets this might be reduced to 0·001; these values do not necessarily represent the best choices, which would depend on the journey distances, the practicable exhaust velocities and permissible specific exhaust powers, etc.

One way in which such a technique might be employed may briefly be described as follows: suppose that the ship concerned consisted of three steps, A, B and C. The first step (A) might use chemical motors for convenience at take-off, and would accelerate the assembly up to a position and velocity sufficient to establish it in an orbit around the Earth. Thereafter, propulsion would be taken over by step (B), having motors of a type giving extremely high exhaust velocity but very low thrust, and hence acceleration; these would be left running over very extended periods and used to accelerate the remaining steps B and C up to escape velocity (or far beyond), and later for gradual braking as the destination planet was approached. It would then be desirable to leave step B established in an orbit around this second planet, effecting a landing by means of the final step C; this might also be a chemical type and would be used for the return take-off. It should then preferably re-connect with step B, which meantime would have been waiting for this operation in its orbit high above the destination planet, ready to propel the assembly back to an orbit around Earth, from which the final landing would be effected by step C alone.

A refinement would be to establish B in an initial orbit around the Earth as a separate prior operation, in which case, step A could be dispensed with—as far as the actual interplanetary mission was concerned—and step C might than be regarded as a sort of tender for all landing and take-off operations. (Earth → B, B → Destination planet, Destination planet → B, B → Earth.) It is conceivable that step B could be serviced and refuelled, back in its final orbit around Earth, by means of other "tender" rockets, and hence remain available for future journeys. Other variants of such a flight-plan will readily occur to readers; rather similar proposals are submitted in another connection, by K. W. Gatland in an article published on page 52 of this *Journal*. The point at issue here is the particular application of such methods in association with propulsion under very low accelerations during the main stages of the flight. The latter low acceleration techniques, furthermore, become reasonable only when *extremely* high exhaust velocities are available; with lower exhaust velocities, the total propellant consumption involved is prohibitive. We have already seen that much higher values of $v_e$ are *permissible* at low accelerations—hence it now remains to investigate whether they are ever likely to be *possible*.

**Direct Methods**

In this connection, perhaps, it is natural for one's thoughts to return to some direct method of applying nuclear energy; in Part I of this series, such hopes were summarily dismissed on the power dissipation argument, but it might be inquired whether this remained valid when only low accelerations were demanded. Since any direct method would involve exhaust velocities approaching 10,000 km./sec., the answer is that the waste energy problem, though

reduced in severity, still remains serious; in looking for some improvement on 10 km./sec., we should do better to be satisfied with an increase of one, rather than two or three, orders of magnitude. Furthermore, there is the very practical consideration that we know of no way of ensuring substantially uni-directional velocities for the recoiling particles from nuclear reactions.

Gamow[11] has suggested, perhaps only half-seriously, a way of overcoming the latter objection, while still retaining a mean exhaust velocity of about 5,000 km./sec., by using radio-active substances as the source of power. He visualizes the use of large plane surfaces spread at right angles to the flight path (rather like the sails on a ship) and coated with a radio-active emitter of $\alpha$-particles. (Helium nuclei.) The recoiling $\alpha$-particles form the exhaust stream, while those emitted forwards or sideways are absorbed in the "sails," or the emitter itself, with resulting dissipation of heat. The emitter must be spread very thinly to minimize this effect, but it is a fundamental drawback to the scheme that rather more than half the total energy release is, always and inevitably, converted into waste heat. Disposal of this would be particularly difficult, because radiation of energy would be the only effective means; normal regenerative cooling methods would be useless, since the rate of expulsion of matter is negligible, and in any case the exhaust particles proceed directly from a fixed source.

Further detailed study shows that, quite apart from other objectives, the accelerations practicable with this scheme would be too low to be useful, while the required "sail" area would be excessive. It is also fundamental to the proposal that *only about 2 per cent. of the reacting material would be ejected to form the exhaust stream.*

Thus, the "characteristic velocity" obtainable would be no better than that from a rocket having about 100 km./sec. exhaust velocity and a normal mass ratio, while the specific exhaust power would be that of a vessel with 10,000 km./sec. as its exhaust velocity; this would be very poor economics.

Slightly more favourable results might be obtained from a modification of the Gamow scheme (to which we shall return later) in which the radio-active source was a suitable $\beta$-emitter (e.g. 65 day Zirconium, $Zr^{95}$), and in which some of the energy was communicated to a source of positive ions, also contributing to the exhaust stream and increasing its momentum. (Simultaneous ejection of particles of opposite charge would in any case be necessary to ensure that emission did not cease.) However, the actual fabrication of the radio-active "sails" would be a very formidable task, arising from a difficulty which has not yet been mentioned here, though it was in Section 2 of Part I; with any built-in radio-active source of power, we should have no means of controlling the rate of production of energy! It is just possibly conceivable that, by "furling" the "sails," the direction and magnitude of the thrust could be controlled, but even when it was reduced to zero, the generation of power would continue, and would then *all* be waste energy calling for disposal.

**The Ion Rocket**

Consideration of such schemes as the above inevitably directs attention towards other, more artificial and more controllable, methods of producing an

exhaust stream of charged particles. Such streams, with almost any velocity up to that of light, can be produced in the laboratory by the acceleration of ions or charged particles in an electrostatic field. These techniques form the basis for what we shall here call the "ion rocket," the jet of which might more correctly be termed an exhaust *beam*, rather than (as formerly) an exhaust stream.

The idea of an ion rocket is not new. Indeed, Oberth devotes a chapter to it in his classic "Wege zur Raumschiffahrt" and it has been the beloved method adopted by writers of fantasy during the past twenty years. All such writers have skirted agilely round the inherent difficulties of the scheme, but we shall now endeavour to rectify their omissions by examining it more critically.

Let us consider ions carrying a single electronic charge ($e$) and having a molecular weight M in units of $A_H$, where $A_H$ = the actual mass (in grms.) of a hydrogen atom. The actual mass of each ion then = $M A_H$; suppose it is accelerated through a total potential difference in the electrostatic field = V.

The velocity of the resulting ion beam, which may then be taken as the exhaust velocity, is given by:—

$$v_e = \sqrt{\frac{2\,V.e}{M.A_H}}$$

and, with V in volts, this becomes:—

$$v_e = 14\sqrt{\frac{V}{M}} \text{ km./sec.} \quad \ldots\ldots\ldots\ldots\ldots\text{(IV. 1)}$$

The above expression IV. 1 has been derived on a non-relativistic basis, but will hold very accurately for all exhaust velocities $< 10^4$ km./sec. It sets the value of the accelerating voltage required to obtain a given exhaust velocity for an ion of molecular weight M. It is interesting to note also the required ion current, which may be obtained through IV. 1 and I. 3. Thus, if I is the ion current in ampères per tonne of accelerated rocket mass, we have:—

$$I = 4{\cdot}9 \times 10^6 \times \frac{av_e}{V} \text{ amps.} \qquad \text{from (I. 3)}$$

and:—

$$V = \frac{M.v_e^2}{196} \text{ volts} \qquad \text{from (IV. 1)}$$

$$\therefore \quad I = 9{\cdot}6 \times 10^8 \times \frac{a}{M.v_e} \text{ amps./tonne mass} \quad \ldots\ldots\text{(IV. 2)}$$

Furthermore, if $m'_p$ is the rate of discharge of "propellant" *per unit accelerated mass*, then we have $m'_p/M$ grm. molecules/sec. It is well known (cf. Faraday's laws of electrolysis) that 1 grm. molecule of singly charged ions carries 96,000 coulombs charge, so it follows that:—

$$I = \frac{96{,}000\,m'_p}{M} \text{ amps.}$$

$$\therefore m'_p = 1{\cdot}04 \times 10^{-5} \times M\,I \text{ grms./sec./tonne mass} \quad \ldots\ldots\ldots\ldots\text{IV. 3}$$

To give an idea of the magnitudes involved, we will take as an example a propulsion unit using *mercury* as a propellant (M = 200·6), working with an exhaust velocity of 100 km./sec. and an acceleration of 0·01 gravities. Under these conditions:—

$$V = 10{,}200 \text{ volts.}$$
$$I = 480 \text{ amps./tonne mass.}$$
$$m'_p = 1{\cdot}00 \text{ grms./sec./tonne mass.}$$

If $v_e$ were increased to 500 km./sec., the figures would become:—

$$V = 255{,}000 \text{ volts.}$$
$$I = 96 \text{ amps./tonne mass.}$$
$$m'_p = 0{\cdot}20 \text{ grms./sec./tonne mass.}$$

The problem of producing high voltages would be far less formidable than that associated with such extremely high ion currents as those above, so it follows that *we should aim at working with the maximum obtainable value of* M, *the maximum permissible* $v_e$ *and the minimum permissible a*. It will have been noticed that IV. 1 is analogous to the corresponding equation II. 6, derived for the thermodynamic scheme, with voltage substituted for temperature as a parameter. Nevertheless, the first of the foregoing recommendations (for a high propellant molecular weight) is exactly opposite to the one applying for thermodynamic motors; the reason is, that whereas high temperatures impose a severe practical limitation, high voltages do not (relatively speaking).

The desirability of a high value of M is a great advantage from the structural viewpoint, since it implies that the best propellants for an ion rocket would have high storage densities and hence make possible the achievement of extremely good mass ratios. For example, if the propellant tanks of V.2 had been filled with mercury (density = 13·6 grms./cm$^3$.), the mass ratio of this rocket would have been over 30, neglecting the increased structure weight which would have been necessary to support the greater propellant weight. Of course, the latter factor would have been very considerable, but the illustration, nevertheless, gives a rough indication of the possibilities.

The immediately obvious means for producing the accelerating electrostatic field for an ion rocket is perhaps the employment of an electrical generator with suitable prime mover. The energy scheme for such a system would become very complex; starting with the energy locked in the atomic nucleus, we should have the following series of transformations from one type of energy to another:–

Nuclear → Particle → Heat → Mechanical → Electrostatic Field → Exhaust

In terms of present practice, we might envisage a fission reactor heating a working fluid to drive gas turbines. The gas turbines (besides driving the compressors for their own working fluid) would supply energy to drive electric generators, which in turn would produce the accelerating electrostatic field and maintain the ion current across it.

It has been pointed out elsewhere in this paper (in connection with the pumping power requirements for thermodynamic type units) that wherever we introduce conventional rotating machinery into a scheme on a large scale, we run a grave risk that the consequent weight and bulk of our power plant will

become prohibitive. It is true that in the ion rocket scheme we are proposing to employ only relatively low values of power rating; this follows automatically from the intention to operate at low accelerations and specific exhaust powers. The word "relatively," however, should be interpreted with caution, since it means only that the values involved would be smaller than for rocket power plants used in the conventional manner, to accelerate against strong gravitational fields. For example, for the case of $a = 0{\cdot}01$, $v_e = 100$ km./sec., considered a short while back, even the *exhaust power* required would still be 4,900 kw. for each tonne mass of the rocket. This is prohibitively high, since the machinery for an output of 4,900 kw. would itself, on present standards, have a mass much greater than one tonne.

The problem is accentuated by the large energy leakages which would occur at each stage in the energy transformation sequence, due to the inefficiencies of each component device. (Thus, at least three times as much heat energy would need to be produced as we could hope to see mechanical energy output from the turbines, and this is only one of several sources of loss.) Apart from increasing the weight and bulk of the "ancillary" machinery, these considerations reveal another serious disadvantage, concerned with the dissipation of waste energy. We have seen that the heat energy generated in the reactor must greatly exceed the final exhaust energy, and all the difference between these two quantities, must, in some manner, be propagated into space. As was the case for the Gamow scheme considered earlier, the mass discharge rate of "propellant" would be of negligible use for this purpose, and it would be inadmissible to use any of the turbine working fluid for cooling. If this were done, the ejection velocity would be low and the coolant consumption high; only brief consideration is necessary to see that this would result in the invalidation of the whole scheme, since the effective exhaust velocity of the rocket is the mean directed velocity of *all* the matter ejected from it, and we should merely be producing a device with a low average value of $v_e$. We should therefore be left, again as in the Gamow scheme, with radiation as the only possible means of disposal for the waste energy, and moreover, would have to employ it under even more adverse circumstances, since our power plant would be a fairly compact affair, in which the waste energy would appear in a concentrated region with correspondingly low radiating efficiency.

It is evident that there would be very formidable difficulties in dealing with even modest specific exhaust powers, and one might be tempted to regard them as quite insuperable. For completeness, however, we shall proceed to discuss one or two other aspects of the ion rocket, since they would be relevant to any variant of the scheme, free from the disadvantages so far mentioned, and which might conceivably be evolved in the future. In the first place, we can safely say that any ion rocket would need to incorporate some means of generating electricity of vastly improved performance and reduced weight as compared with anything known to-day. It would be required to provide potential differences of $10^5$ to $10^6$ volts and present slow, low frequency, generators would never be capable of this. Some form of high speed, high frequency, electromagnetic machine, or some radically new design of electrostatic generator, could perhaps be regarded as possibilities.

We have also seen that very large ion currents would be needed in the exhaust beam. The design of an ion source, capable of separating ions at the necessary rate, would present another very severe problem. It might conceivably take the form of a chamber containing the propellant, in the gaseous phase, at a low pressure. In this gas it would be necessary to produce an intense degree of ionization, and this might be done by the direct action of nuclear recoil particles. In a scheme incorporating a nuclear reactor, the ionization chamber could be made part of this (the high ambient temperatures would also be useful to vaporize the propellant), and its walls lined with thin $U^{235}$ foil. Each fission fragment passing into the gas would produce about a million pairs of ions.

In the past, it has sometimes been maintained that an ion rocket could not continue to emit charged particles indefinitely, because the accumulation of charge on the vessel would eventually set up a retarding field capable of preventing further emission. This would be true if ions or particles of only one sign were emitted, but the difficulty could easily be overcome by not following such a course. For example, in the case of a rocket emitting positive ions, large heated cathodes should be provided from which copious electron discharges could take place. Any tendency for an accumulation of negative charge on the rocket would then be counteracted instantly by the acceleration of electrons away from the rocket in the resultant field; so long as the cathode emission was great enough, the maintenance of electrical neutrality would be automatic.

### The Ion Rocket : A More Direct Method

In view of the many attractive features of the ion rocket, we shall not leave the subject without inquiring whether the complex energy scheme previously described could not be simplified in some way, so that the bulky and heavy secondary power plants could be eliminated, and at least some of the cooling problems along with them. It may be said at once that such a simplification is possible, at least in theory.

In the scheme described before, the introduction of the thermal and mechanical stages was for the purpose of establishing an electrostatic field and maintaining it against a large ion current flow. Each ion accelerated through the field took energy from it, and this had to be replaced by the generating machinery, which had to move an ion of opposite charge against the field. However, charged particles of very high kinetic energy are emitted in nuclear reactions and it is certainly possible that they might be made to maintain the energy of a retarding field without going through all the complex chain of events previously specified. Theoretically, one should be able to employ a simple series of energy transformations, of the form:—

Nuclear Energy → Particle Kinetic Energy → Electrostatic Field Energy → Exhaust Kinetic Energy.

This can be illustrated by the following example: let us suppose that we have an electrostatic field of total potential V volts and let us further suppose that into this field we introduce both electrons of initial kinetic energy = V

electron volts, and also positive ions of zero initial energy and unit electronic charge. We shall assume that the electrons are retarded and the positive ions accelerated, both types of particle being introduced at the "origin" of the field. Now, so long as the field is maintained, and the influence of the moving charges on the field is negligible, we shall have the following state of affairs:—

(i) Each electron will yield its kinetic energy to the field, emerging with zero energy—in other words, its original *kinetic* energy is converted into *potential* energy.

(ii) Each positive ion, starting with an initial *potential* energy of V electron volts, will have this converted into kinetic energy as it is accelerated through the field, and will emerge with a final *kinetic* energy of V electron volts.

Thus, each electron supplies its original kinetic energy to the field, which in turn passes it on to the ion. The original energy must, of course, be supplied to the electrons (either by ancillary devices again, or as the direct result of nuclear reactions) and the necessary source of positive ions must also be provided. However, so long as electrons and positive ions cross the field in equal numbers, it will be maintained at constant strength without the addition of further energy from external sources.

If the total energy of a particle in this field is denoted by E ($E = V.e \times 10^7$ ergs), then the initial momentum of an electron in the field is given by

$$\psi_- = \frac{1}{c}\sqrt{E(E + 2m_o c^2)}$$

where $m_o$ is the rest mass of the electron and $c$ is the velocity of light. In the case of the positive ion, the *final momentum* is given by:—

$$\psi_+ = \sqrt{2\,Em_+}$$

where $m_+$ is the mass of the positive ion. The relativistic expression given for the electron is necessary because in all practical cases the initial electron velocity will be a large fraction of that of light. No such refinement is necessary in the case of the "slow" moving positive ions.

The ratio of final positive ion momentum to initial electron momentum is now given by:—

$$\frac{\psi_+}{\psi_-} = \sqrt{\frac{2\,m_+ c^2}{E + 2\,m_o c^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (IV.\,4)$$

In all cases which interest us, this ratio has the order

$$\sqrt{\frac{m_+}{m_o}},$$

hence (where $M_+$ is the molecular weight of the positive ion) we have:—

$$\frac{\psi_+}{\psi_-} \simeq \sqrt{2{,}000\,M_+}$$

The field therefore acts as a *momentum transformer*, increasing the momentum of the particles leaving the field, over those entering it, by the factor $\sqrt{2{,}000\ M_+}$ (approx.). There is no violation of the law of conservation of momentum, because the gain in particle momentum is balanced by an equal and opposite gain in field momentum, which is communicated to the conductors upon which the field terminates (and which constitutes the propulsive effect).

The $\beta$-emitting scheme briefly discussed earlier in this Part (following the reference to the Gamow proposals) would constitute a simple application of this momentum transformer principle. Of course, the example which we have given is purely hypothetical. In practice we should have considerable complication due to the negligible electrostatic capacity of a rocket in space, the continuous distribution of energy of electrons emitted in $\beta$-disintegration and other factors. (It would be pointless to attempt to go into great detail at this premature stage.) We also saw that in that case there would be the overriding disadvantage of being unable to control the rate of energy production in the fixed radio-active source. However, there is no reason why the same basic principle should not be applied along different lines, free from this difficulty.

## 7.—Conclusions

It seems desirable to conclude this series by a brief summing-up of the results achieved in all the preceding sections. These may conveniently be submitted as six points, viz.:—

(i) While chemical rocket motors have a long development ahead of them, at the end of which time they will be capable of far more spectacular achievements than to-day, they are, nevertheless, likely to prove inadequate for true interplanetary flight on any basis of reasonable economy of effort. (Part I.)

(ii) The hope of achieving interplanetary flight must therefore be centred largely on some application of atomic energy, though the radiation difficulties involved in such a development indicate that chemical motors may still play an important subsidiary rôle. (Part I.)

(iii) The most promising way of applying nuclear energy to rocket propulsion, at any rate initially, seems to lie in the extension of methods already envisaged for industrial power generation, i.e. by using nuclear energy to heat up a secondary working fluid. This follows from the prohibitive difficulties associated with the dissipation of waste energy in any more direct scheme—assuming that it was required to produce sufficient thrust to combat strong gravitational fields. (Parts I and II.)

(iv) On the basis of present published information, the immediate practical prospects of systems such as those described in (iii) are not very encouraging. Systems of the same basic principle, but differing in detail execution, can be shown to involve formidable problems arising from the need to operate at excessive temperatures or pressures (or both), while the heat transfer and propellant pumping requirements

are extremely severe. The development is therefore likely to be long and difficult, but the fundamental principles are clear, and there are indications (some plausible, others highly conjectural) of directions along which final success might lie. (Parts III and IV.)

(v) The more pessimistic views expressed in (iv) are really valid only for the most ambitious aim of producing a propulsion unit suitable for interplanetary flight. (Exhaust velocity $\simeq$ 10 km./sec.) It seems quite reasonable to expect that a more modest type of nuclear rocket motor might be developed in the fairly near future. This would probably employ a solid "fast-neutron" reactor and either hydrogen or ammonia as propellant; with an operating temperature limited to something less than 2,000° K. (probably nearer 1,000° K.) this would show little improvement in exhaust velocity over improved chemical motors of the near future. The overall performance of a rocket to which it was fitted would show still less gain, due to the greater weight and bulk of the nuclear motor, and to the extra weight of radiation shielding which it would require. In fact, such a unit might have no practical value at all. Nevertheless, from such an initial experiment the knowledge and experience needed for the final perfection of the idea would almost certainly gradually be forthcoming. (Part III.)

(vi) There are also indications of a different way in which nuclear energy might be applied to rocket propulsion, under the rather specialized conditions of flight at very low accelerations, starting from an initial orbit and not from a planetary surface. This scheme (here called the "ion rocket") would involve the acceleration of an exhaust stream of charged particles, up to very high velocities of ejection, by the medium of an electrostatic field. It has very great possibilities (under the specialized conditions noted, which greatly reduce the waste energy disposal problem otherwise associated with extreme exhaust velocities), but its realization must await the development of a technique not requiring the use of conventional prime movers and electrical generators. (Part IV.)

REFERENCE

(1) *Atomic Energy in Cosmic and Human Life*, by George Gamow. *Camb. Univ. Press.*

*The paper on page* 71 *was read to the B.I.S. on December* 11, *to open the Symposium on "The Problem of Interplanetary Flight." The other papers in this series, given by Mr. L. R. Shepherd and Mr. A. V. Cleaver on December* 11 *and January* 15, *will not be published, as they are largely covered in the articles by the same authors of which the concluding instalment appears above.*

# THE DYNAMICS OF SPACE-FLIGHT

By Arthur C. Clarke, B.Sc.

## 1.—Introduction

The number of books on astronautics is now very considerable, but they fall rather sharply into two categories—the "popular" or semi-technical, and the highly mathematical. This paper is an attempt to fill the gap between these extremes, and to give a reasonably accurate quantitative treatment of many of the problems of astronautics without advanced mathematics. Indeed, it is hoped that many of the conclusions reached can be understood without much trouble by those with no mathematical training at all.

The subject divides itself naturally into three sections: first, the motion of a body in the Earth's gravitational field; then the problem of the lunar voyage; and finally, true interplanetary journeys. The cases are of increasing difficulty and complexity and will therefore be dealt with in this order.

It may be as well to point out that this discussion is perfectly general and does not presuppose any particular form of propulsion—chemical rocket, atomic rocket, or even rockets at all. To travel from one body in space to another involves the expenditure of a definite amount of energy: from this point of view it does not matter in the least by what technical means the journey is made. It is true that the rocket is the only conceivable form of interplanetary locomotion at the moment: but even if the anti-gravity screen beloved of early science-fiction writers appears, it will still have to obey the same fundamental laws.

These laws are extremely simple and have been well understood since their formulation by Newton nearly 300 years ago. It is, indeed, a curious thought that there is probably nothing in this paper which would be unfamiliar to Newton—whereas such relatively far less spectacular aspects of our subject as aerodynamics or thermodynamics would be almost incomprehensible to him.

Astronautics is a branch of celestial mechanics, the science dealing with the movement of heavenly bodies. Spaceships will obey the same laws, and will hence move along the same sort of paths, as planets and comets—except during those very short periods of time when they are under power. It is a fortunate fact that, with accelerations which the human body can withstand comfortably, a spaceship need operate its motors for only about 10 minutes to attain velocities which would take it anywhere in the Solar System—even on journeys that might last for decades. It follows, therefore, that for practically the whole duration of any voyage a spaceship would be "inert," like any heavenly body, entirely under the control of the gravitational forces in the surrounding space.

## 2.—Gravitational Fields

The gravitational field with which we are most familiar, and from which all our journeys must commence, is the Earth's, which at sea-level produces an acceleration on a falling body of 9·81 metres per second per second (32·2 feet per sec. per sec.) Table I shows how the value of $g$ varies for the most important bodies in the Solar System, and it will be seen that there are only two planets

on which human beings would feel heavier than they do on Earth. To bring the meaning of these figures home more vividly, the second column shows how long it would take to fall 4·9 metres from rest on each of these bodies—the distance one falls in the first second on Earth.

TABLE I

| Body | Gravity E = 1 | Time to fall 4·9 m. (sec.) | Escape velocity (km./sec.) | Circular velocity (km./sec.) |
|---|---|---|---|---|
| Sun .. .. .. | 28 | 0·2 | 618 | 437 |
| Mercury .. .. | 0·26 | 2·0 | 3·5 | 2·5 |
| Venus .. .. | 0·90 | 1·1 | 10·4 | 7·3 |
| Earth .. .. | 1 | 1 | 11·2 | 7·9 |
| Moon .. .. | 0·16 | 2·5 | 2·3 | 1·6 |
| Mars .. .. | 0·38 | 1·6 | 5·0 | 3·6 |
| Phobos .. .. | 0·001* | 30* | 0·01* | 0·01* |
| Jupiter .. .. | 2·65 | 0·6 | 60 | 42·5 |
| Ganymede .. | 0·2* | 2* | 3* | 2* |
| Saturn .. .. | 1·14 | 0·9 | 36 | 25 |
| Titan .. .. | 0·2* | 2* | 3* | 2* |
| Uranus .. .. | 0·96 | 1·0 | 22 | 15·5 |
| Neptune .. .. | 1·0 | 1·0 | 23 | 16 |

* Approximate figures.

The gravitational field of a body falls off with distance according to Newton's inverse square law—if one doubles the distance from the centre, "g" is reduced to a quarter, and so on. Thus the fields of the planets are effective only over very small distances, astronomically speaking. Fig. 1 shows the variation of

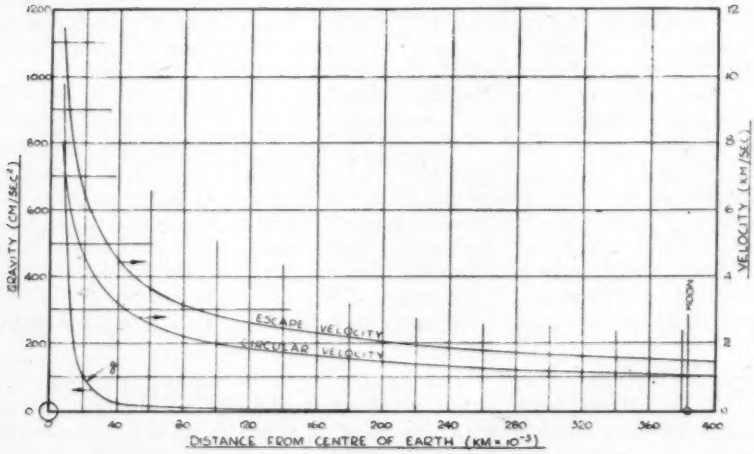


FIG. 1.

Variation of gravity, and escape and circular velocities, with distance from Earth's centre.

the Earth's field with distance. Despite the fact that beyond 100,000 kilometres it is too small to be presented accurately on the graph, it never reaches zero however far away one goes. Even at 385,000 kilometres it is sufficient to keep the not inconsiderable mass of the Moon chained to its orbit!

When a body is lifted against the Earth's gravitational field, the work that has to be done equals the product of the vertical distance and the force. But since the force is steadily decreasing, it follows that the work done over equal distances is also decreasing, according to the same inverse-square law. The *total* work that has to be done in lifting a body from the Earth's surface to a point where gravity is negligible (to infinity, as the mathematician would put it) is therefore proportional to the total area beneath the "g" curve in Fig. 1. This can be calculated very easily, and leads to the important and surprisingly simple result that for unit mass:—

$$E = gR$$

where R is the radius of the Earth.

This means, for example, that to lift one ton completely away from the Earth (R = 4,000 miles) we must do 4,000 mile-tons of work. *The task is therefore exactly equivalent to that of climbing a mountain 4,000 miles high, assuming that gravity remained constant.* Perhaps this brings home more vividly than anything else the order of magnitude of the energies involved.

The formula $E = gR$ applies to all other bodies, if $g$ and R stand for the appropriate surface gravities and radii. In this way we can calculate that to escape from the Moon is equivalent to climbing vertically 180 miles under one terrestrial gravity, a height not much greater than that attained by V.2.

The Earth's gravitational field, therefore, may be regarded as producing a sort of valley or pit 4,000 miles (6,360 kilometeres) deep out of which we have to climb if we wish to travel to other worlds. The walls of the pit are very steep near the beginning, but rapidly flatten out with increasing distance (Fig. 2). At the Moon's distance the gravitational slope is very gentle: it is never *perfectly* flat, but beyond about a million kilometres it is so nearly level that scarcely any more work need be done in moving away from the Earth. As far as energy considerations are concerned, we have reached "infinity," though by astronomical standards we are still very near the Earth.

If we happen to be going towards the Moon, we presently come across its private gravitational pit, only 278 kilometres (180 miles) deep, and with much more gently sloping sides. Fig. 2 shows very clearly how relatively easy it is to leave the Moon, and how important it may be as a base for expeditions to other planets. Though so close, astronomically speaking, it is really nine-tenths of the way to infinity.

There are two ways of climbing out of a valley. The usual method is to proceed up the slope at a low but more or less constant speed, exerting a fairly steady effort all the time. The second method, not unfamiliar to cyclists, is to build up such a speed at the bottom of the hill that one can then relax and rely on one's momentum to carry one to the top without any further effort—trading velocity for height.

Both methods are, in theory, possible for a spaceship leaving the Earth.

If a rocket, for example, had unlimited power supplies, it could climb to the stars at a steady 100 miles an hour. But this slow, steady departure would require an enormous expenditure of energy, since most of the machine's effort would be wasted merely maintaining its position. (The extreme case of this is the rocket just balanced on its exhaust, which burns the whole of its fuel getting nowhere.) We are therefore forced to consider only the case in which a sufficient initial velocity is built up, in a relatively short distance, to enable the rocket to make the rest of the journey on momentum alone.

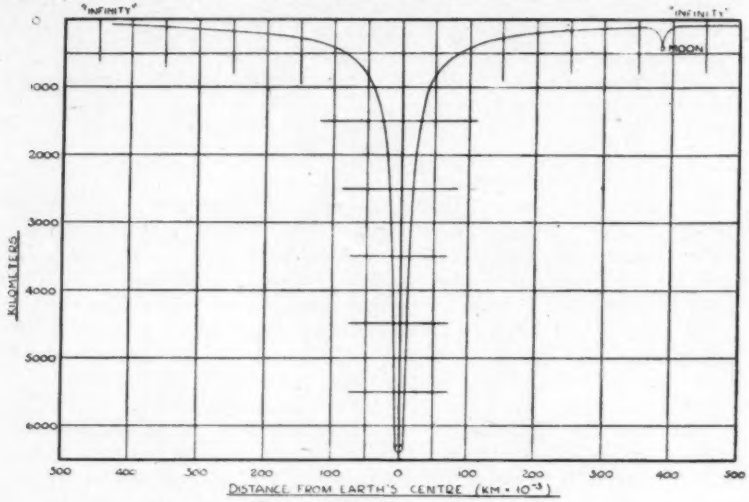


FIG. 2.

Potential Energy Diagram of Earth–Moon System.

The velocity needed to enable us to "coast" up our 4,000-mile-high hill is almost exactly 25,000 miles an hour (11·2 km./sec.). This is the famous "velocity of escape," and its physical meaning is nothing subtler than this. A body projected vertically from the Earth at 11·2 kilometres (or 7 miles) a second would travel outwards, always slowing down, but would never fall back. At a lower speed, it would come to rest before reaching the top of the "hill," and would come falling down the slope again. It would return to Earth with exactly its initial speed, as would any body projected up a frictionless slope with a velocity insufficient for it to reach the top.

### 3.—Escape and Circular Velocities

Every planet has its characteristic escape velocity, usually quoted for the surface of the body. Escape velocity falls off with increasing height: as might be expected, the velocity needed to reach the top of the "gravitational slope" is reduced if one starts some way from the bottom. The rate of decrease is rather slow, depending inversely on the square *root* of the distance. (See Appendix.)

Related to escape velocity is the conception of circular velocity. This is the velocity a body needs, not to escape from a planet, but to circle it like a moon. At the Earth's surface this velocity is about 18,000 miles an hour (7·9 km./sec.). If a body reached this speed in horizontal flight just outside the atmosphere the outward centrifugal force would exactly balance gravity. It would circle the Earth once every 90 minutes or so. At greater heights the velocity required is naturally less, the variation with distance being the same as for escape velocity. In fact, at any point the escape velocity is equal to $\sqrt{2} \times$ circular velocity.

Fig. 1 shows the variation of the Earth's escape and circular velocities with distance: it will be seen that they fall off very much more slowly than does "g". Fig. 3 shows the value of circular velocity for points close to the Earth, and also

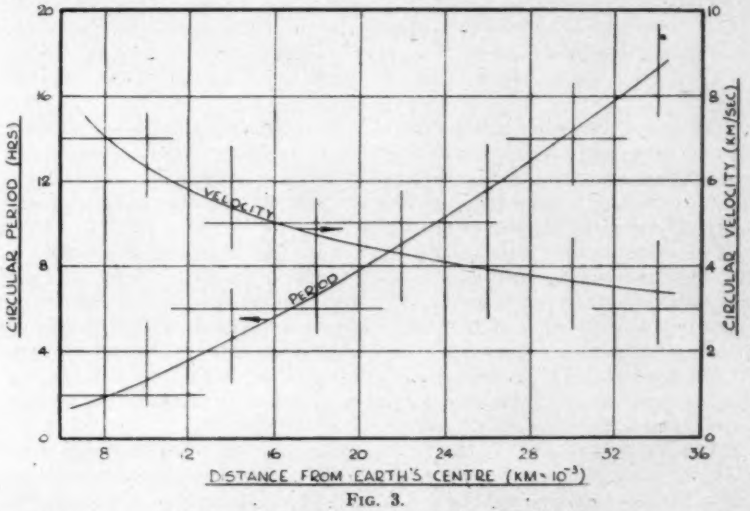


FIG. 3.
Period and Velocity in Circular Orbit round Earth.

the period of revolution of a body in a circular orbit. These orbits will probably be the first to be of practical importance in astronautics.

Table I lists the escape and circular velocities for the chief bodies in the Solar System. They range from 60 km./sec. for Jupiter down to about 10 metres/sec. for Phobos, the inner moon of Mars. It would be possible to jump completely away from a body a little smaller than this: Phobos' "gravitational pit" is only about five *metres* deep, as against the Earth's 6,360 kilometres!

We are now in a position to discuss the requirements for a voyage from the Earth to the Moon. Looking at Fig. 2 again, we see that the velocity needed to reach the Moon from the Earth is a little less than that needed to reach "infinity." The difference, however, is only about a tenth of a kilometre a second, so we will assume that the full velocity of escape, 11·2 kilometres a second, is required.

A spaceship given this velocity in the direction of the Moon would slowly lose speed until it came almost to rest about 40,000 kilometres from the Moon. Then, as it began to enter our satellite's "gravitational pit" it would begin to accelerate again. If unchecked, it would reach the Moon at a little less than that body's velocity of escape, 2·3 kilometres a second. The ship's motors must therefore be used to neutralize this speed, and hence the *absolute minimum* velocity requirement for the journey is 11·2 + 2·3 or 13·5 kilometres a second (30,000 miles an hour). The ship would, of course, never actually reach this speed: but it must be potentially capable of doing so.

This figure is a theoretical minimum which must be exceeded in practice owing to (*a*) air resistance at take-off, (*b*) "gravitational losses" due to the retarding effect of the Earth's field and (*c*) margins for navigational corrections, which might be considerable at the lunar end of the voyage. These additional figures are rather indefinite and depend a good deal on particular cases. In general, they should not exceed 20 per cent., making the total "velocity budget" for the one-way lunar voyage about 16 kilometres a second (36,000 miles an hour).

The air resistance loss, though it is the one most often mentioned, is in fact, the least important. A rocket leaving Earth is travelling relatively slowly in the atmosphere, and on a large ship the velocity loss due to frictional drag would be only a fraction of a kilometre a second—a negligible quantity compared with the requirements for the rest of the voyage.

The return journey is the same as the outward one, but with this difference, that the Earth's atmosphere may be used to produce a certain amount of frictional braking at the end of the voyage. Ignoring this, the requirement for the round trip would be 2 × 16 or 32 kilometres a second (72,000 miles an hour). Allowing for atmospheric braking, it would be about 30 kilometres a second (67,000 miles an hour), or perhaps a little less. Once again it should be emphasized that the maximum velocity the ship would ever actually reach would be less than a third of this.

We have been able to use this relatively simple treatment in the case of the Earth–Moon voyage because both bodies are at the same distance from the Sun, and so the Sun's gravitational field acts on them equally and may, therefore, be ignored. If we wish to consider true interplanetary journeys, however, we can no longer do this. Not only must our spaceship escape from one planet and lower itself safely on to another, but it must also do work either moving outwards against the Sun's gravitational field, or decelerating itself after falling down the solar field. It is therefore necessary to consider how this field varies across the orbits of the planets.

### 4.—The Sun's Gravitational Field

The Sun's gravitational field obeys exactly the same laws as the Earth's: the only difference is that it is far more intense and is effective over a far greater volume of space. Escape velocity at the surface of the Earth is 11·2 kilometres a second: at the surface of the Sun it is no less than 618 kilometres a second. Thus the energies needed to leave the two bodies are of an altogether different

order of magnitude. The Earth's 6,360-kilometre-deep "gravitational pit" seemed quite impressive: but to escape from the Sun is equivalent to climbing, under one gravity, out of a pit 20,000,000 kilometres (12,000,000 miles) deep!

Luckily for astronautics, this "pit" is so very narrow that even Mercury, the innermost planet, is far up on the shallow, higher slopes. All the planets, in fact, are within a quarter of a million kilometres of the top, and as a result the velocities needed to go from one orbit to another are in most cases less than those needed to escape from the planets themselves. This is certainly very fortunate. One could easily imagine Solar Systems with very massive suns in which it might be quite simple to escape from a planet and go to its satellite, whereas the journey from one planet to another might be almost impossible.

We will now construct an "energy diagram" of the Solar System on much the same lines as we have already done for the Earth and Moon. This time, however, we will measure the depth of the "gravitational pit" in terms of the velocity needed to escape from it at any point, since it is this in which we are primarily interested. To escape from the Sun requires a velocity of 618 kilometres a second, which gives the maximum depth of the pit. To escape from the orbit of the innermost planet, Mercury, requires only a tenth of this—68 kilometres a second. But Mercury's orbital speed is already 48 kilometres a second: hence the additional velocity needed is 20 kilometres a second. This additional or excess velocity, which we will call "transfer velocity," is much less for the outer planets. In the Earth's case it requires only an extra 12·3 kilometres a second above orbital speed to reach infinity.

The left-hand side of Fig. 4 shows these transfer velocities for points out to the orbit of Jupiter. If the planets *had no gravitational fields of their own*, these would be the velocities needed by a spaceship to leave them and to escape completely from the Solar System.

But, of course, the planets have their own gravitational fields, each with its characteristic escape velocity. Thus we can, to a good degree of approximation, represent the true state of affairs by attaching to the main curve subsidiary "icicles" whose depths, in kilometres a second, are the escape velocities of the planets concerned.

This type of diagram was first constructed, as far as we know, by Dr. Robert S. Richardson, though we believe he employed energy units instead of velocities as ordinates. Physicists have, of course, used such figures for a long time to represent the potential barriers around atomic nuclei.

The resulting picture is not much like one's ordinary idea of the Solar System: but it is much more useful for astronauts. It shows, for example, the surprising fact that a journey to the outer planets could start more easily from Mercury than from Venus! It also demonstrates very vividly the difficulty of getting away from Jupiter, should one be unfortunate enough to be born there. Mercury is far further away from the Sun, dynamically speaking, than is the surface of Jupiter!

To sum up, Fig. 4 indicates that the velocities needed to travel from one orbit to the next are, in general, less than those needed to escape from the planet of origin. The diagram even gives a rough idea of the *total* velocity needed for an interplanetary journey, from surface to surface, but more accurate

results require a fuller treatment which we will briefly discuss in the next section.*

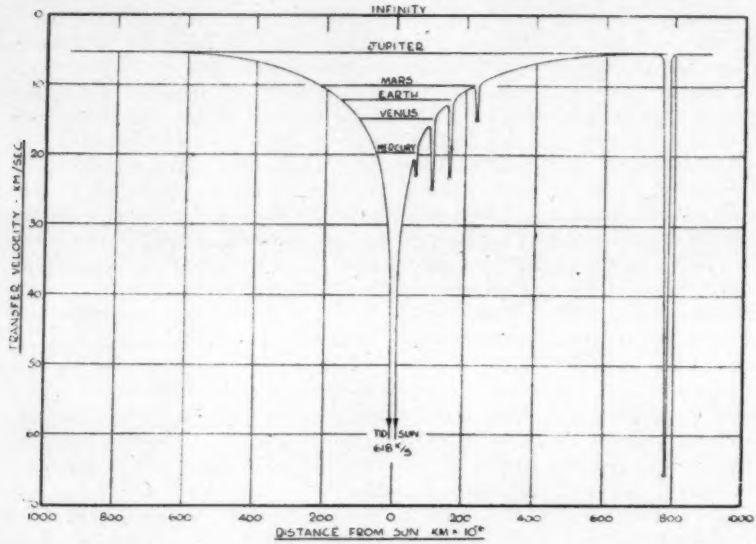


FIG. 4.

Energy Diagram of Solar System, in terms of Required Transfer Velocities.

## 5.—Orbits and Trajectories

So far, our treatment has been somewhat abstract: we have not considered the actual shapes of the paths that spaceships must follow, but only their initial velocities of projection. To fix ideas, we will first discuss possible orbits in the Earth's field.

We have already seen that a body travelling horizontally just outside the atmosphere at 7·9 kilometres a second would maintain itself in a circular orbit, never falling to Earth. At any lesser speed, it would return to the planet, though it might travel half-way round the world before doing so. But what of speeds *greater* than 7·9 kilometres a second?

Fig. 5 shows what happens in these cases. As the speed of projection increases, the orbit elongates into an ellipse of greater and greater eccentricity. As the velocity of escape—11·2 kilometres a second—is approached, the ellipse becomes larger very rapidly indeed. At exactly 11·2 kilometres a second it opens out, as it were, into a parabola, and the body never returns.

* A warning should be given here. Fig. 4 only gives the velocities needed to travel from one orbit to *infinity*. It cannot be used directly to find the speeds needed to get from one orbit to *another orbit*, though it gives a rough idea of their magnitudes.

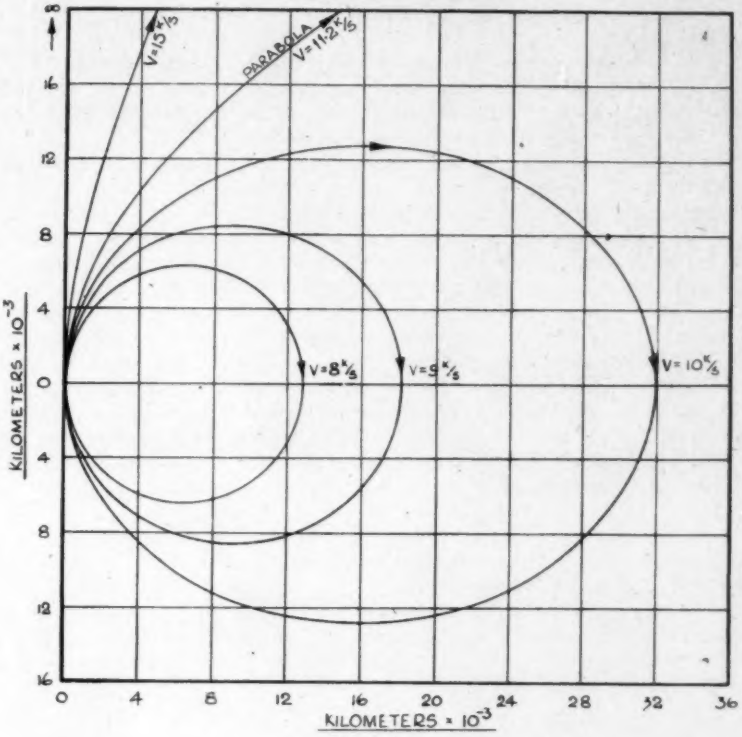


FIG. 5.
Orbits in Earth's Field.

It should therefore be noted that a spaceship will escape from Earth at 11·2 kilometres a second whether its direction of motion is horizontal or vertical or at any intermediate angle.

When the velocity exceeds 11·2 kilometres a second, the orbit is an hyperbola which becomes more and more nearly a straight line as the velocity approaches infinity.

These orbits are of fundamental importance because they arise whenever a body moves in a gravitational field, whether it be that of the Earth or the Sun. Planets, comets and asteroids give all possible types of closed orbit from almost perfect circles to very elongated ellipses. It has often been suggested that some meteors and comets may travel on hyperbolic paths, so that they pass through our system only once: but it is difficult to prove this, since (as will be seen from Fig. 5) all the paths are very similar at the nearest point to the central force.

From the astronautical point of view the elliptical paths are the most important, since they can be used to link one circular orbit to another. Fig. 6 (*a*)

shows such an orbit touching the paths of, say, two "space-stations" $S_1$ and $S_2$ circling the Earth.

The body in the elliptical orbit will touch the space-station orbits at A and B: but at A it will be travelling *faster* than $S_1$ while at B it will be travelling *more slowly* than $S_2$. Small velocity increments would therefore be needed at A and B to change from one type of orbit to another.

If one is in a circular orbit, and *increases* the speed slightly, the orbit becomes elliptical, lying outside the original circle—as happens at A. If one *decreases* the speed, the orbit becomes an interior ellipse, as at B.

Exactly the same argument applies for journeys between planets. Fig. 6 (*b*) shows the actual velocities involved in a journey from Earth to Venus (or vice versa). It will be seen that the transfer velocities where the orbits touch are quite small. They are within the range of present-day rockets: a V.2 starting from space in the Earth's orbit could reach Venus quite easily with full payload!

(At this point we recall an instructive mistake made by the author of a space-travel story many years ago. In this tale an interplanetary journey was made by sending a rocket to an asteroid which happened to be passing close to the Earth and which, owing to its elliptical orbit, gave its passengers a "free lift" to their destination. Unfortunately, of course, the presence of the asteroid would have made no difference at all. Once the spaceship had matched the asteroid's velocity—which it would have to do to make a landing—it would have travelled on exactly the same elliptic orbit whether the asteroid was there or not. So the expedition would have gained nothing but a few acres of probably rather uninspiring scenery.)

This type of orbit, which just grazes two planetary orbits, is by no means the only possible one. It will, however, be almost intuitively obvious that it requires the minimum energy. In the case of the Venus journey, we obtain a total "velocity budget" as below:—

| | km./sec. |
|---|---|
| Escape from Earth .. .. .. .. .. | 11·2 |
| Earth orbit to voyage orbit .. .. .. .. | 2·5 |
| Voyage orbit to Venus orbit .. .. .. .. | 2·7 |
| Landing on Venus .. .. .. .. .. | 10·4 |
| | 26·8 |

Gravitational losses and navigational corrections would bring this figure up to at least 30 kilometres a second. The journey would last about 146 days, apart from the actual landing-time at Venus.

For Mars the requirements are as follows, assuming mean distance between the planets. (As the orbit of Mars is somewhat eccentric, the figures vary slightly.)

| | km./sec. |
|---|---|
| Escape from Earth .. .. .. .. .. | 11·2 |
| Earth orbit to voyage orbit .. .. .. .. | 2·9 |
| Voyage orbit to Mars orbit .. .. .. .. | 2·7 |
| Landing on Mars .. .. .. .. .. | 5·0 |
| | 21·8 |

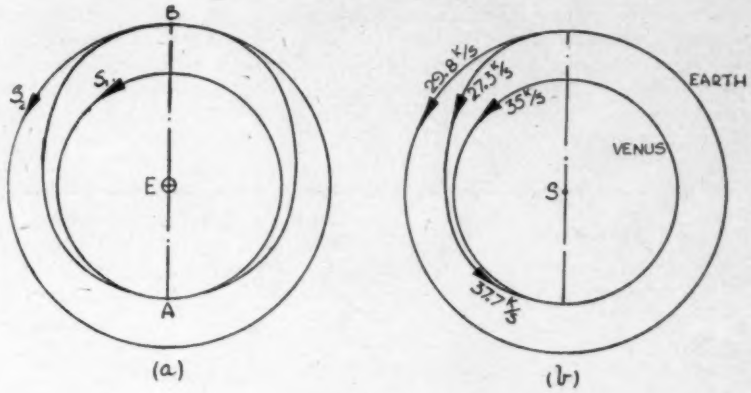


FIG. 6.
Tangential Ellipses.

This would be at least 25 kilometres a second in practice—considerably less than for the voyage to Venus. But the journey would last longer—237 days.

These times of transit, though long, are not impossibly so. They could be reduced indefinitely by travelling in more eccentric orbits, or even along hyperbolic paths. Such orbits, however, would cut across the paths of the planets at steep angles and so would require very high transfer velocities. The fuel requirements for such journeys would thus be multiplied by very large factors indeed, making them out of the question for the first and perhaps even the second generation of atomic spaceships.

Orbits of this type would be necessary for journeys to the outer planets, which would last many decades if the tangential paths were employed.

### 6.—Summary

We may now summarize our main results in Table II, which shows the theoretical velocities needed for various typical journeys, as well as estimates of what these values may be in practice. In some cases the latter figures may

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turn out to be unduly pessimistic, since they make no allowance for atmospheric braking. Some authorities consider that a landing on Earth (and presumably on Venus) could be made almost entirely by air-braking, with very little use of the rockets. We hope that this is the case, but have felt it safer to ignore the possibility.

TABLE II

| Mission | | Theoretical velocity* | Approximate actual value.† | |
|---|---|---|---|---|
| | | km./sec. | km./sec. | m.p.h. |
| One-way journeys. | Orbit round Earth .. | 8 | 10 | 22,000 |
| | Escape from Earth .. | 11·2 | 13 | 29,000 |
| | Earth to Moon .. .. | 13·5 | 16 | 36,000 |
| | Earth to Mars .. .. | 22 | 25 | 56,000 |
| | Earth to Venus .. .. | 27 | 31 | 70,000 |
| Return journeys. | Earth–Moon–Earth (no landing). .. | 22·4 | 25 | 56,000 |
| | Lunar return trip (with landing). .. | 27 | 32 | 72,000 |
| | Earth–Mars–Earth (no landing). .. | 28 | 32 | 72,000 |
| | Mars return trip (with landing). .. | 44 | 50 | 110,000 |
| | Earth–Venus–Earth (no landing). .. | 28 | 32 | 72,000 |
| | Venus return trip (with landing). .. | 54 | 62 | 140,000 |

* Ignoring air resistance and gravitational losses. † Including allowance for losses.

## 7.—Conclusion

Our survey has now gone as far as is possible without employing mathematics of great complexity and extreme ugliness. Most of the problems in astronautics can only be discussed by numerical, step-by-step calculations, and no exact general solutions are possible. The conclusions we have reached must therefore be regarded as first approximations to the truth, but in most cases they are very good approximations indeed—correct, that is, to a few per cent. As such, they are quite sufficient to give a good idea of the general nature of the problem, which we now hand on to those engineers who are brave—or rash—enough to tackle it.

## Appendix

For convenience in reference, some of the more important results in interplanetary dynamics are summarized below.

**Earth's Gravitational Field**

If $g$ is surface gravity, $r$ is distance from Earth's centre, R is radius of Earth, then gravity $g_1$ at any point $r$ is, by inverse square law,

$$g_1 = gR^2/r^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{I}$$

Hence work done in moving unit mass to infinity from the Earth's surface is

$$\int_R^\infty \frac{gR^2}{r^2}\,dr = gR \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{II}$$

This is the result used in Section 2 and is true for all bodies if $g$ and R are given their appropriate values.

At the velocity of escape, the kinetic energy of the projected body must equal $gR$, i.e. $\frac{1}{2} v_e^2 = gR$

Hence $$v_e = \sqrt{2gR} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{III}$$

Similarly the velocity of escape at any point $r$ is given by

$$v_r = \sqrt{\frac{2gR^2}{r}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{IV}$$

Circular velocity is given by the condition that at $r$, the outward centrifugal force due to the body's motion must equal the inward gravitational force.

Hence $$\frac{v^2}{r} = \frac{gR^2}{r^2}$$

or $$v = \sqrt{\frac{gR^2}{r}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{V}$$

$$= \sqrt{gR} \text{ at Earth's surface.}$$

Hence escape velocity at any point equals $\sqrt{2}$ times circular velocity at that point.

The height obtained by a body projected vertically from the Earth's surface (ignoring air resistance) is given by

$$H = \frac{2gR^2}{2gR - v^2} - R \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{VI}$$

This becomes infinite as $v \to \sqrt{2gR} = 11{\cdot}2$ km./sec.

**Orbits**

The velocity at any point in an orbit under a central force is given by:—

$$v^2 = \mu\left(\frac{2}{r} \pm \frac{1}{a}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{VII}$$

the minus sign being taken in the elliptic case, the plus in the hyperbolic case. $r$ is the distance from the centre of force, $a$ the semi-major axis, and $\mu$ is a

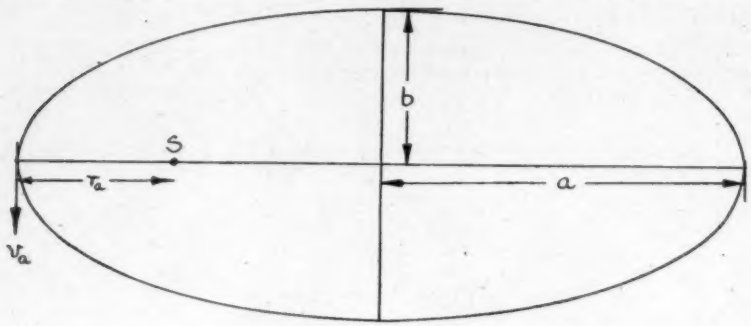


FIG. 7.
Ellipse: leading dimensions.

gravitational constant $= gR^2$ ($= 4 \times 10^5$ km.$^3$/sec.$^2$, very nearly, for the Earth).

In the parabolic case this reduces to

$$v^2 = \frac{2\mu}{r} \quad \text{.....VIII}$$

If the perigree or perihelion velocities and distances $v_a$, $r_a$ are known, we may then calculate $a$ from equation VII, which becomes

$$a = \frac{\mu}{(2\mu/r_a) - v_a^2} \quad \text{.....IX}$$

The semi-minor axis $b$ is given by:—

$$b = \frac{v_a r_a}{\sqrt{(2\mu/r_a) - v_a^2}} \quad \text{.....X}$$

Equations IX and X enable us to calculate the orbits in Fig. 5, while from equation VII we can calculate the $v_a$ needed to travel from one circular orbit to another. In this case the major axis $2a$ will clearly be the sum of the radii of the two circular orbits.

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# KNOW YOUR COUNCIL

L. R. SHEPHERD, B.Sc., A.Inst.P. Born 1918 in a mining village of South Wales, and later attended the Secondary School at Ferndale, Glam. Was an undergraduate at University College, London and obtained his B.Sc. (Special) in Physics in 1940. During the following five years was a research assistant on a Government project at the Royal Society Mond Laboratory, Cambridge. In January, 1946, took up post-graduate studies as a research student of St. Catharine's College, where, until recently, he was engaged on research in nuclear spectroscopy at the Cavendish Laboratory.

Mr. Shepherd tells us that his interest in Interplanetary Flight dates from the early age of 11, and this he attributes to the influence of a science fantasy story in a juvenile magazine. At such an impressionable age, the assimilation of such ideas as flight to other planets led to the choice of a scientific career, and although the ensuing twenty years have somewhat reduced the optimism of early youth, they have by no means dampened his enthusiasm for the pursuit of the objective of space flight.

Became a member of the B.I.S. in the early part of 1935, but did not take part in any of its pre-war activities. Was present at the first post-war meeting of the Society in 1945, and became a member of the Council and the Society's Technical Director in 1946.

Mr. Shepherd holds the view that several decades must pass before the flight of manned rockets becomes a practical proposition, because he considers that this achievement must rest upon the eventual application of nuclear power to rocket propulsion.

He also believes that one of the main aims of the B.I.S. should be to stimulate the interest of rocket engineers and nuclear energy workers into seeking an early combination of their two fields of work, thereby laying the foundation upon which space flight must one day be built.

G. V. E. THOMPSON, B.Sc., A.R.C.S., A.R.I.C. Born 1920 and educated at Great Yarmouth Grammar School. After obtaining a Royal Scholarship in Physics and Mathematics, he studied Chemistry at Imperial College, graduated in 1941, and worked with Roneo Ltd., for 5 years as Assistant Works Chemist, 2 years as Research Chemist. He is now Senior Assistant in the Information Department, British Non-Ferrous Metals Research Association, being engaged in editorial work on the Association's publications, abstracting, translating, etc.

In addition to his chemical and metallurgical interests, Mr. Thompson has been a student of chemical engineering for many years, and is also a keen linguist, with a knowledge of Russian. He is a member of the London Area Committee of the Association of Scientific Workers, the representative of London University on the Board of Governors of Hackney L.C.C. Secondary Schools, and an abstractor for "British Abstracts."

His interest in interplanetary travel was awakened when he was 12, and resulted in an essay describing a spaceship powered by T.N.T.! This literary effort earned him the nickname of "The Mad Scientist" from his schoolfellows.

He joined the re-formed B.I.S. in 1946, and has served on the Council since that year, being also a member of the Society's Technical Advisory Committee.

# ABSTRACTS

EDITED BY J. HUMPHRIES

### Chemical Propellants—Stability of Mononitromethane

(F. Bellinger, H. B. Friedman, W. H. Bauer, J. W. Eastes and W. C. Ball. *Ind. & Engng. Chem.*, July, 1947, Vol. 40, No. 7, pp. 1320–3, 1324–31, illus., tabs., graphs)

Although mononitromethane is here considered as a source of power for launching buzz-bombs it also has possibilities as a rocket propellant. Its ability to detonate under certain conditions, however, places serious restrictions on its use, and although this tendency to detonate can be greatly reduced by the addition of certain materials—for example, gasoline, methanol or amyl acetate—it cannot be eliminated. The second paper discusses its use, together with oxygen, as a propellant.

### What's Ahead for Rockets?

(*Aviation Week*, July 5th, 1948, Vol. 49, No. 1, p. 23.)

Review of the answers given to the Guggenheim Foundation opinion survey of leading experts in the rocket industry. Amongst other things it was recommended that an analysis of the non-military applications of satellite and space-ships should be undertaken and that an interplanetary flight project should be sponsored.

### Oscillographic Analysis of the Non-Acoustic Functions of the Vertebrate Ear

(Dr. Otto Lowenstein, *Nature*, April 24, 1948, Vol. 161, No. 4095, pp. 652-4.)

New knowledge about the mechanism of the balancing organs has been obtained by application of Adrian's oscillographic technique, which has already shown that information on fluid motion in the semicircular canals is conveyed to the brain by variations in frequency of electric discharges along the nerve-branch supplying the organ. The author proved that the discharge frequency is proportional to the acceleration, but that accelerations of less than 3 degrees per sec. per sec. fail to be registered.

Dr. Lowenstein has now applied the same technique to the utricle, a small cavity which shares the same circulating fluid with the canals. Experimenting on the ray fish, the most suitable animal for the purpose, he finds that this organ registers any out-of-level position of the head by the same mechanism of changing the discharge frequency along the nerve. Not only this, but the utricle informs the brain of linear and angular accelerations and of rotation at constant speed.

[Abstractor's Note: Dr. Lowenstein does not mention that a smaller version of the utricle, called the saccule, is also present, and apparently differs from it only in that the membrane containing the sense organs is vertical. If the nerve mechanism is similar, as seems likely, then in conditions of "no gravity" the brain would be informed by the utricle that it was level, by the left saccule that it was tilted to the right, and by the right saccule that it was tilted to the left. This, then, would be the nature of the "conflicting messages to the brain" mentioned by R. A. Smith in his lecture on the Man-Carrying Rocket (see *Journal of the B.I.S.*, May, 1948, Vol. 7, No. 3, p. 102).—A.E.S.]

## Carbon or Graphite as a Liner for Combustion Chambers of Rocket Motors

(J. A. Slyh *et al.* Four reports published by U.S. Dept. Comm., Off. Tech. Serv. at $1.00 each)

PBL 79494, January, 1947, 7 pp. Aluminium-graphite combinations; investigation of coatings of tantalum carbide, silicon and chromium on graphite for preventing oxidation.

PBL 79495, February, 1947, 6 pp. Graphite bodies containing powdered aluminium or chromium.

PBL 79498, March, 1947, 7 pp. Mixtures of graphite and selected metals.

PBL 79500, April, 1947, 7 pp. Mixtures of graphite and aluminium.

## Nutrition of Athletes

(*Nature*, August 7, 1948, Vol. 162, No. 4110, pp. 207-8.)

A symposium of papers read to the Nutrition Society on July 17, dealing with oxygen and food requirements during strenuous exercise, is summarized. At an easy running pace, 4 litres of oxygen per minute are required, but the heart cannot pump this amount into the body indefinitely; one litre per minute is near its upper limit for a prolonged period.

Athletes at the 1936 Olympiad showed an average food intake of 7,300 calories daily, but this was shown to be grossly in excess of their actual needs. Dr. G. H. Bourne suggested, as a probable explanation, that the Vitamin B complex plays an important part in carbohydrate metabolism, and in severe exercise the average daily requirement might amount to 22·5 mgm. daily, or 15 times the normal. Thus, the large intake of protein may be necessary merely to secure sufficient vitamin, and could be avoided by supplying the vitamin in more concentrated form.

## Performance and Ranges of Application of Various Types of Aircraft-Propulsion System

(Cleveland Lab. Staff. *N.A.C.A. Tech. Note No.* 1349, August, 1947, 67 pp., tabs., refs. + 67 pp. figs.)

A group of papers on the comparison of the performance of six aircraft-propulsion systems—(1) the compound engine, (2) the turbine-propeller engine, (3) the turbojet engine, (4) the turbo-ram-jet engine, (5) the ram-jet engine, and (6) the rocket engine. It is shown that the compound engine which has the greatest weight per unit thrust and also the lowest specific fuel consumption, gives the longest range. As the speed is increased it is necessary to progress to engine types that provide greater thrust per unit weight and per unit frontal area, generally at the cost of an increased specific fuel consumption.

At supersonic speeds the range of the airplane increases with increased flight speed and altitude for each of the propulsion systems considered. The ram-jet gives the longest range. The rocket engine because of its low weight per unit thrust and its compactness, gives the highest disposable load, but because of its extremely high specific propellant consumption gives the shortest

range. For a rocket plane with a gross weight of 43,900 lb., delivering a thrust of 40,000 lb., a range of 1,387 miles is indicated at a flight speed of 5,000 m.p.h. and an altitude of 100,000 ft.

### An Extension of the Flow and Continuity Equations of a Moving Gas to Include the Existence of Gas Sources and the Entrainment of Solid or Fluid Particles

(Fcap. *Acta Phys. Austriaca*, 1947, Vol. 1, No. 1, pp. 89-97. In German)

Equations for the one-dimensional flow of gases are extended to allow for the pressure of "gas sources," also combustible liquid droplets and solid particles. General methods of solution are outlined. Results may have some application to theories of rocket propulsion and internal ballistics (from *Phys. Abstr.*, Sect. A., Vol. 51, No. 608, p. 206).

### Rockets and Their Fuels

(W. Ley. *Coast Artillery J.*, Nov.–Dec., 1947, Vol. 90, No. 6, pp. 30–33, illus. and Jan.–Feb., 1948, Vol. 91, No. 1, pp. 25–29, tabs.)

A general review, the first part dealing with solids, the second part with liquids. The second part deals with the choice of propellants, both monopropellants and bipropellants, but unfortunately, contains several errors.

### The Anti-aircraft Guided Missile

(Lt.-Col. W. L. Clay. *Coast Artillery J.*, July–Aug., 1948, Vol. 91, No. 4, pp. 15–18, illus.)

A general discussion of the anti-aircraft guided missile system. (1) The launcher must provide guidance initially during acceleration period until the missile-booster combination is stable in flight. It must also be small and light. (2) The booster accelerates the missile up to design speed as rapidly as possible—solid propellant rockets are most suitable for this. (3) The missile consists of a ram-jet or rocket power plant, control equipment and a warhead. (4) Ground control system is either of the beam rider or command system.

### Probability That a Meteorite Will Hit or Penetrate a Body Situated in the Vicinity of the Earth

(G. Grimminger. *J. Appl. Phys.*, Oct., 1948, Vol. 19, No. 10, pp. 947–56, figs., tabs., refs.)

When a body is situated at sufficiently great altitudes (about 200 km. or above) it is exposed to impact by the meteorites which enter the earth's atmosphere. A preliminary attempt is made to estimate the probability that a body situated in the vicinity of the earth will be hit by a meteorite and, when a hit does occur, to estimate the metal plate thickness necessary to prevent perforation by the impact of meteorites of different sizes. For stainless steel skin thicknesses ranging from 0·05 to 0·02 in. it is necessary to consider meteorites as small as those corresponding to magnitude 8 to 11, respectively. In general, however, it is found that for meteorites which are large enough to present a

perforation hazard the probability of a hit is negligibly small, particularly if the body is not exposed to meteoritic impact for excessively long periods of time.

### Diabatic Flow of a Compressible Fluid

(B. L. Hicks. *Q. App. Maths.*, Oct., 1948, Vol. 6, No. 3, pp. 221–37, refs.)

The theory of diabatic flow (i.e. non-adiabatic) is needed to provide proper theoretical interpretations of present basic experimental studies of combustion aerodynamics. The author's purpose in the present series of papers (of which the one under review is the first) is to describe the principal characteristics of steady diabatic compressible flow. The treatment applies to both thin and thick burning regions and to sub-sonic and super-sonic flow conditions if it is understood that algebraic equations should be added whenever necessary to express conservation of energy, mass and momentum across flow discontinuities. The theory does not apply generally where viscous effects may be important, as in the interior of detonation fronts, ignition within boundary layers, etc. Results deduced are compared with their counterparts in adiabatic flow.

### Introduction to the Problem of Rocket-powered Aircraft Performance

(H. Reese Ivey, E. W. Bowen, jun., and L. F. Oborny. *N.A.C.A. Tech. Note No.* 1401, December 1947, 46 pp., 18 diag.)

The title of this report is somewhat misleading, because it does not treat the performance of a rocket-powered aircraft, but of the true rocket-projectile.

The well-known formulae for thrust, all-burnt velocity, propulsive efficiency, nozzle area ratio are deduced, followed by a consideration of the vertical flight in vacuum, for one-, two- and three-stage rockets. The expression which is given here for the altitude in vacuum of a single rocket, is the same as found in Malina's I.Ae.S. paper of March, 1938.

The influence of drag and $g$-variation on this height is briefly examined, and finally, the "elliptic" range as function of the launching velocity and of the ratio of fuel-weight to initial-weight is calculated. However, the range-formula which is used to estimate the performance of rockets is not valid for these, but for a projectile fired from a gun.

Considering that the propulsive part of a rocket-trajectory may be relatively large, especially with step-rockets, the range-charts are of very approximate nature.

Nevertheless, the theoretical performance possibilities of rocket-projectiles are clearly presented in this interesting report. G. de K.

### Secrets of the Shaped Charge

(G. B. Clark. *Ordnance*, July–Aug., 1948, Vol. 33, No. 169, pp. 49–51, illus.)

Although shaped charges were used to great effect in the bazooka and artillery projectiles during the last war, readers will probably be most interested in them through the recent attempts in the U.S. to fire them from V.2 rockets in order to produce artificial meteorites. This article explains clearly in non-technical terms the "Munroe effect" on which the design of the shaped charge is based.

# REVIEWS

## An Outline of Stellar Astronomy

(By Peter Doig, F.R.A.S. Hutchinson & Co., Ltd., 47, Princes Gate, S.W.7. 168 pp., index, illus., 10s. 6d.)

For those interested in the progress of astronomy and of science generally, this book comes with an up-to-date account of the strides Stellar Astronomy is taking. It does not purport to be a text book on the subject; on the other hand it is not aimed at the layman or as Mr. Doig puts it "for readers with slightly more knowledge than that necessary for perusal of 'popular' astronomical literature."

The extent of the subject matter cannot be summed up better than with the book's opening paragraph. "This book gives an outline of the state of knowledge of the constitution, dimensions, motions and distribution in space of the stars and nebulae." This matter is logically laid out in three parts, "The individual star (observational data,)" "The nature of a star," and "The stellar universe." This is not so successful as one might think, as there is a lot of overlapping in chapters in different parts. For instance, the chapter "The causes of stellar variability" in Part II has very little to add to that already said in chapter "Binary stars, variable stars and novae" in Part I.

A very good feature is the use made of the appendices. These cover subjects which crop up constantly in the body of the book, and give a more mathematical treatment of such subjects as "The explanation and derivation of astrophysical terms," "Stellar temperature and distribution of energy in spectra," "Modern indirect methods of parallax estimation," "Approaches and collisions between stars" *inter alia*. These appendices, with a liberal number of tables, give a considerable amount of concise information, and ample opportunity for checking up statements for oneself. The book is completed with an introduction giving the definitions of the chief astrophysical terms, a glossary and an index.

The illustrations do not, however, uphold the excellence of the book, the printing of the photographs being very poor; for instance, that of the chief types in the Harvard spectral sequence giving the appearance of a regular row of lines in all classes, and those of star-fields and nebulae a cross-hatched effect which obscures and blurs even quite extended features. We hope this will be remedied in the next edition, as undoubtedly it will be, for there should be a great demand for this interesting and useful book. M. P. D.

## Lunar Catastrophic History

(*Geology Applied to Selenology*. Vol. III.) (By J. E. Spurr. The Rumford Press, Concord, New Hampshire, U.S.A., 1948. 253 pp., index, diagrams.)

This work, the third in Mr. J. E. Spurr's series, more than maintains the high standard of interest set by its predecessors. Those who have read the first two volumes—*Geology Applied to Selenology* and *Features of the Moon*—will be familiar with his ideas, but the present book, though intended mainly to develop and elaborate the author's theories, is more or less complete in itself.

The old volcanic theory of Nasmyth and Carpenter was palpably inadequate in many respects, but Spurr, though retaining vulcanism as the main force in the moulding of the Moon's surface, tells a far more convincing story; he has taken great care to leave no surface feature unexplained, and many individual formations are described in detail. The craters and their distribution, the maria, the clefts, the enigmatical lunar rays—all are accounted for in plausible fashion, and it is hard to find any serious flaws in the author's reasoning. Many of the suggestions put forward are highly novel and ingenious. For instance, the gullies on the slopes of some of the great craters, such as Aristillus and Eratosthenes, are attributed to running water that fell from a water-vapour cap (or "atmodome") in the form of rain. Spurr has obviously no use for the Proctor-See meteoric hypothesis of crater formation, and the now discredited glaciation theory is not mentioned at all.

The author frequently stresses the importance of the Earth's influence upon the moulding of the lunar surface, and has no doubt that the moon was once a part of our planet. The suggestion that the marked central-meridianal ridge of the moon is due to terrestrial tidal attraction may seem highly speculative, yet this ridge is hard to account for in any other way.

For such a detailed volume there are very few misprints or mis-statements, but one or two criticisms should be made.

It is a pity that the author has not included a brief glossary of his new terms for the benefit of those who have not read his previous works. Expressions such as "caldera-crater" and "necfault" will not be found elsewhere.

Some of the accepted lunar names have been deliberately shortened—Mare Serenitatis, for instance, becomes "Serenitas"—and these alterations seem to be pointless and unjustifiable. Moreover, many other names are wrongly spelt. Cardanus is referred to as "Cardenus"; Gueriké, "Guerike"; Picard, "Pickard"; Parry, "Perry"; Rabbi Levi, "Rabbi Levy"; Torricelli, "Torrecelli"; Réaumur, "Reaumur"; and Epigenes, "Epigines." Dionysius is spelt "Dionysus" on page 7, though correctly given later on, and on page 214 (last line of paragraph 2) Alphonsus becomes "Alphonso."

The illustrations are invariably printed with the north at the top. This does not, of course, affect their accuracy; but the impulse of the practised lunar observer will certainly be to turn them upside-down!

Nearly all the measurements of crater diameters and mountain heights are taken from Neison and Webb, two notoriously unreliable sources. While no really reliable set of figures has yet appeared, the values given by Goodacre (B.A.A. Memoirs, Vol. 32, 2) are far better than Neison's. It should, however, be pointed out that the author (p. 37, footnote) comments upon the unreliability of the values he has had to use.

General errata are as follows:

P. 3, line 2.—It is misleading to speak of the moon's "virtual cessation of rotation." This cessation is relative to the earth only.

P. 4, para. 5.—Theophilus cannot be said to be the centre of a major ray-system.

P. 6, para. 3, and p. 173, line 3.—The name "De Morgan" is universally applied to the small craterlet, not to any larger semi-ruined formation.

P. 7, line 5.—For Phoclydes read Phocylides.

P. 59, line 10.—For Mesoselene read Teleoselene.

P. 70, footnote.—The name "Palus Putredinis" is universally accepted.

P. 245, line 1.—It is by no means certain that the moon is now totally airless. It may well retain a tenuous atmosphere.

These, however, are but minor blemishes upon a work that must be considered one of the most important contributions to selenology to have appeared in recent years. The author has expended a prodigious amount of labour, and has put forward a very strong case. Before we make our first attempt to reach the moon, it is essential for us to find out all we can about its surface; and for this reason alone "Lunar Catastrophic History" should be studied by every person seriously interested in interplanetary flight. P. A. M.

## FORTHCOMING MEETINGS

April 4, 1949 (Monday). A lecture on "Interplanetary Flight," by A. V. Cleaver, to the Derby Branch of the R.Ae.S.

April 23, 1949 (Saturday). A **Film exhibition** at the **N.W. District Centre** of the B.I.S. "Rocket Flight" and "Airborne Rockets," at Adult Education Institute, 49 Lower Mosley Street, Manchester, 2, Lancs.

April 28, 1949 (Thursday). "Rocket Propulsion and Interplanetary Flight," by A. V. Cleaver. To the Manchester Branch of the Royal Aeronautical Society, Reynolds Hall, Manchester College of Technology, 7.30 p.m.

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